INVESTIGATING SMART CLASSROOM ACOUSTICS UTILIZING COMPUTER MODELING

BY

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A Thesis Presented to the

DEANSHIP OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the

Requirements for the Degree of

MASTER OF SCIENCE

In

ARCHITECTURAL ENGINEERING

DECEMBER 2002

UMI Number: 1411743

ProQuest Information and Learning Company
300 North Zeeb Road
P.O. Box 1346
Ann Arbor, MI 48106-1346

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To My Parents

ACKNOWLEDGEMENT

All praises to ALLAH subhana-wa-ta'ala, who granted me the grace and strength to complete this work. Peace and blessing of Allah be upon his last Prophet Mohammad (SAW).

Acknowledgement is due to King Fahd University of Petroleum and Minerals for the support and facilities provided for the completion of this thesis.

I wish to express sincere appreciation and profound gratitude to my thesis advisor Dr. Adel Abdou for his valuable guidance, remarkable assistance and continuous support throughout the course of this study. He gave me countless hours of attention for this accomplishment inspite of his busy schedule. Working with him was indeed a wonderful experience which I thoroughly enjoyed. Thanks are also due to my thesis committee members, Dr. Ismail Budaiwi and Dr. Thamir Al-Rugaib for their suggestions and keen interest at every stage of this work.

Profound thanks are also due to all the faculty and staff of the department for their encouragement and support. I am grateful to Architectural Engineering department for providing excellent computing facility. I would also like express sincere appreciation to Mr. Sharieff for assisting me with the field measurements & providing me continuous support.

I would also like to thank my colleagues and fellow students especially Mr. Khurshid, Dr. Abdul Hameed, Mr. Muneer and Mr. Muneeb Asif for the help and motivation they provided me throughout the course of this study.

Last but not the least, I am grateful to my parents and family for their moral support, encouragement and prayers without which this work would not have been possible.

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THESIS ABSTRACT

STUDENTS NAME	:	**MIR SABEER HAMID**
TITLE OF STUDY	:	**INVESTIGATING SMART CLASSROOM ACOUSTICS UTILIZING COMPUTER MODELING**
MAJOR FIELD	:	**ARCHITECTURAL ENGINEERING**
DATE OF DEGREE	:	**DECEMBER 2002**

Good listening conditions are essential in classrooms. Students are greatly handicapped when the classroom acoustics are marginal or poor affecting the comprehension of delivered speech. Poor acoustical ambience affects teachers as well; talking over noisy classrooms can be exhausting to the teacher and to his or her willingness to dialogue with the students. With the evolution of new generation of classrooms referred to as 'Smart Classrooms' meant for better and interactive learning, a large number of PC's and instructional equipment are integrated into the classroom which generate noise effecting Speech Intelligibility (SI) within a smart classroom. The objective of this study is to investigate the impact of sound-absorbing material treatment on the acoustical conditions of typical classroom in-terms of material placement and absorption characteristics and at the same time, study the effect of noise generated by instructional equipment on SI.

For better understanding of the influencing acoustical parameters and the assessment of equipment noise, measurements are carried out in conventional as well computer classrooms of King Fahd University of Petroleum and Minerals, Dhahran. Supported by the results of acoustical measurements, a typical smart classroom model is simulated varying the surface treatment to achieve an overall best configuration of sound-absorbing material placement and absorption characteristics. The effectiveness of the described layout is verified, comparing it with the Acoustical Society of America (ASA) recommendations for surface treatment in typical classrooms. The impact of various Background Noise (BN) levels on SI noticed from measurements is studied by simulating the derived best configuration under various BN conditions.

The results highlight the significance of surface treatment with sound absorption materials on improving smart classroom acoustics. Enhancement in speech conditions are achieved from the derived best overall configuration of surface treatment. Similar results are revealed as the formulated layouts are compared with ASA recommendations. The detrimental effect of noisy environment on SI is investigated and the necessity of standardizing noise level as per ASA specification for classroom acoustics is emphasized. The outcome of this research can be used as guidelines by educational establishments for retrofitting of existing classrooms as well as for new projects.

MASTER OF SCIENCE DEGREE

KING FAHD UNIVERSITY OF PETROLEUM AND MINERALS
DHAHRAN, SAUDI ARABIA
DECEMBER 2002

ملخص الرسالة

إسم الطالب	:	مير ، سابير حامد
عنوان الرسالة	:	دراسة الصوتيات في "الفصول الدراسية الذكية" باستخدام النمذجة بالحاسب الآلي.
التخصص	:	الهندسة المعمارية
تاريخ الدرجة العلمية	:	ديسمبر 2002م

إن وجود بيئة صوتية جيدة توفر الاستماع الجيد أثناء الحديث، والتخاطب في الفصول الدراسية يعتبر من الأمور المهمة والضرورية لتحقيق الأداء الوظيفي المطلوب. فعندما تكون البيئة الصوتية في الفصل سيئة يجد الكثير من الطلاب صعوبة في الاستماع مما يؤثر على الإدراك الصوتي، وبالتالي عدم القدرة على الفهم، بالإضافة إلى ذلك فإن المعلم قد يتأثر سلباً أو إيجاباً بالبيئة الصوتية ، فالتحدث في فصول ذات مستوى ضوضاء عالٍ يكون مجهداً للمتحدث، وبالتالي قد يؤثر سلباً على رغبته في تبادل الحديث مع الطلاب. ومع ظهور جيل جديد من الفصول الدراسية يُشار إليها "بالفصول الذكية" والتي تحتوي على العديد من مصادر الضوضاء الإضافية مثل أجهزة الحاسب الآلي، ومعدات العرض المختلفة تأثرت البيئة الصوتية مما أثرعلى جودة الاستماع.

تهدف هذه الدراسة إلى التحقق من تأثير معالجات المواد الماصة للصوت بالإضافة إلى تأثير الضوضاء الصادرة من التجهيزات التعليمية على الاستماع وإدراك الحديث. فقد تم إجراء العديد من القياسات الميدانية في عينة من الفصول الدراسية التقليدية وأيضاً معامل الحاسب الآلي بجامعة الملك فهد للبترول والمعادن بالظهران بهدف التعرف على العوامل الصوتية المؤثرة. وقد أظهر تقويم وتحليل نتائج القياسات مدى تأثير معالجة الحوائط على سلوك الصوت ومستوى الضوضاء في الفصول الدراسية. فبقياس ومقارنة مستوى الضوضاء الضمني (Background Noise) في حالة تشغيل وعدم تشغيل الأجهزة والمعدات التعليمية أمكن تحديد مدى تأثير عمل هذه التجهيزات على مستوى و المحتوى الترددي للضوضاء الموجودة. كما تم نمذجة "فصل دراسي ذكي" باستخدام برنامج " ODEON " وذلك لدراسة تأثير معالجات الحوائط والسقف من ناحية كفاءة الامتصاص الصوتي وأماكن توزيعها لتحقيق أفضل تكوين (Configuration). و بمقارنة النموذج الناتج للفصل الدراسي مع النماذج المختلفة من الفصول الدراسية المُقترحة من قبل الهيئات العلمية المعنية في مجال الصوتيات تبيَّن أن النموذج المقترح يحقق الأداء الصوتي المطلوب، ولتحديد تأثير الضوضاء الضمني على سماع وإدراك الحديث في الفصل الدراسي المقترح فقد تم دراسة تأثير مستويات مختلفة من الضوضاء الضمنية.

تخلص الدراسة إلى وضع نموذج لمعالجة الأسطح في الفصل الدراسي الذكي نوعاً ومكاناً للحصول على بيئة صوتية جيدة. كما تقترح الدراسة حدود مستوى الضوضاء المسموح به في مثل هذه النوعية من الفصول الدراسية. ويُتوقع أن يستفيد المعماريون والهيئات التعليمية من نتائج الدراسة عند إعادة التصميم الداخلي للفصول القائمة أو المزمع تحويلها إلى فصول دراسية ذكية أو في مشروعات المباني التعليمية الجديدة.

درجة الماجستير في العلوم
جامعة الملك فهد للبترول والمعادن
الظهران - المملكة العربية السعودية
ديسمبر 2002م

CHAPTER 1

1.0 INTRODUCTION

In spite of the development in knowledge exchange media and educational setup, classrooms still continue to play a vital role in academic exchange and learning. Information exchange between student and teacher is a two way process with vocal communication as the basic medium. Identically in a learning environment; right visual, acoustical and thermal qualities facilitate the effective exchange of knowledge and enhance levels of comprehension. Classrooms are rarely designed without optimum light, as visibility is essential; similarly, with speech being the main communication medium, audibility is also essential. It is necessary to have an appropriate acoustical ambience within the classroom. We never use classrooms that have low visibility or are dark, but we may use spaces for teaching which are acoustically deficient.

Architects and facility planners are quite adept at specifying appropriate lighting levels for classrooms. Required ventilation change rate and indoor environmental temperature controls are always included in any building design. Just as the effect of changes in these design parameters on room occupants can be predicted, the effect of room finishes and indoor noise on the ability to verbally communicate in the room can be predicted. Teaching in a room with poor acoustics is not only analogous to reading in dim light, but inappropriate acoustical design exaggerates the difficulty of communication between teacher and student.

The physical elements and the room proportions dictate the acoustical characteristics of a classroom. Excessive external and internally generated noise, reverberation time, echo and other features interfere with speech intelligibility resulting in reduced understanding and therefore reduced learning. A study in the United States [1] showed that the speech intelligibility rating in classrooms is 75 percent or less which means that out of every four words, the listener misses one word. In situations like these, the students face problems and the basic aim of modern education is lost. This makes it essential to check and verify enclosures for education and to model and simulate modern classrooms to enhance their acoustical characteristics.

1.1 Important Issues

The main issues supporting the necessity for acoustical modeling & simulation of classrooms are listed below.

1) Good acoustics is essential for all listening-based learning. This is especially important for young people. In addition, people with hearing or learning difficulties and non-native listeners are greatly handicapped when the classroom acoustics are marginal or poor.

2) Contrary to the perception of lighting, people do not always know when the acoustics are below the optimum conditions for hearing. Therefore, except for rooms that have conspicuously poor acoustics, one cannot reliably determine whether the acoustics are adequate by asking the listeners. This highlights the requirement for objective assessment.

3) Good acoustics are important for the teacher as well. Talking over a noisy classroom can be exhausting and discouraging to the teacher and to his/her willingness to dialogue with students.

4) Sound reinforcement can be usefully integrated in large classrooms and in special education rooms and multimedia halls but should not be seen as a substitute for good natural classroom acoustics.

5) Good acoustical conditions in classrooms are very beneficial and the investments in improving acoustics in classrooms are associated with financial gains.

1.2 Smart Classrooms

Classrooms are changing from conventional isolated units to more connected places with improved visual communications. A new generation of high technology classrooms known as 'smart classrooms' are becoming a necessity at universities. These classrooms integrate computer education with the latest presentation and multimedia facilities making the classrooms more interactive. It becomes easier for faculty to make presentations, show computer outputs and interact with the student stations with full screen displays.

The utilization of this technology brings more equipment into the classroom, such as computers at every student station, large screens for visual display, networking equipment etc. that may affect the quality of sound perceived by the occupants. Thus, for optimal acoustical performance of these new specialized classrooms (smart classrooms), it is essential to evaluate them for speech intelligibility.

1.3 Objectives

The goal of this research is to:

- **Investigate the acoustical characteristics of the modern classroom (i.e. smart classroom) as an emerging education facility in terms of the basic physical requirements that yield good acoustical conditions for Speech Intelligibility (SI).**

In order to achieve the above stated goals three sub-objectives are also formulated which are as follows:

- Evaluation of acoustical quality of the existing conventional classrooms at King Fahd University of Petroleum and Minerals (KFUPM).
- Study the effect of noise from computers and permanent instructional equipment on classroom acoustics.
- Investigation of the impact of surface treatment on classroom acoustics utilizing state-of-the art computer modeling and simulation software (ODEON 5.0).

Investigation is carried out to achieve the best overall sound-absorbing material configuration in terms of material characteristics and placement on the classroom surfaces resulting in enhanced SI. In addition to this, the identification of acceptable Background Noise (BN) for such specialized classrooms is also studied.

1.4 Methodology

In order to convert a classroom into a smart classroom with the required acoustical performance, it is essential to investigate the acoustical characteristics for acceptable SI of the conventional classrooms as a first step. For this purpose, five university classrooms of varied proportions and finishing treatment are selected for measurement and evaluation. These classrooms as a sample represent the majority of classroom typology existing within the university. The research would be carried out in the following steps as also shown in Figure 1.1.

1. Literature study and case studies on issues like:
    - Speech Intelligibility
    - Measurement techniques
    - Modeling classroom acoustics, geometry & configuration
    - Configuration and requirements of Smart classrooms
2. Measurements of acoustical quality for speech intelligibility in selected sample classrooms.
3. Analysis and evaluation of the measurements.
4. Modeling a smart classroom utilizing the most accurate & widely used computer model.
5. Investigation of acoustical characteristics required for good speech intelligibility in smart classrooms.
6. Identification of the most influencing parameters and formulation of guidelines for better listening conditions and enhanced acoustical ambience in modern classrooms.

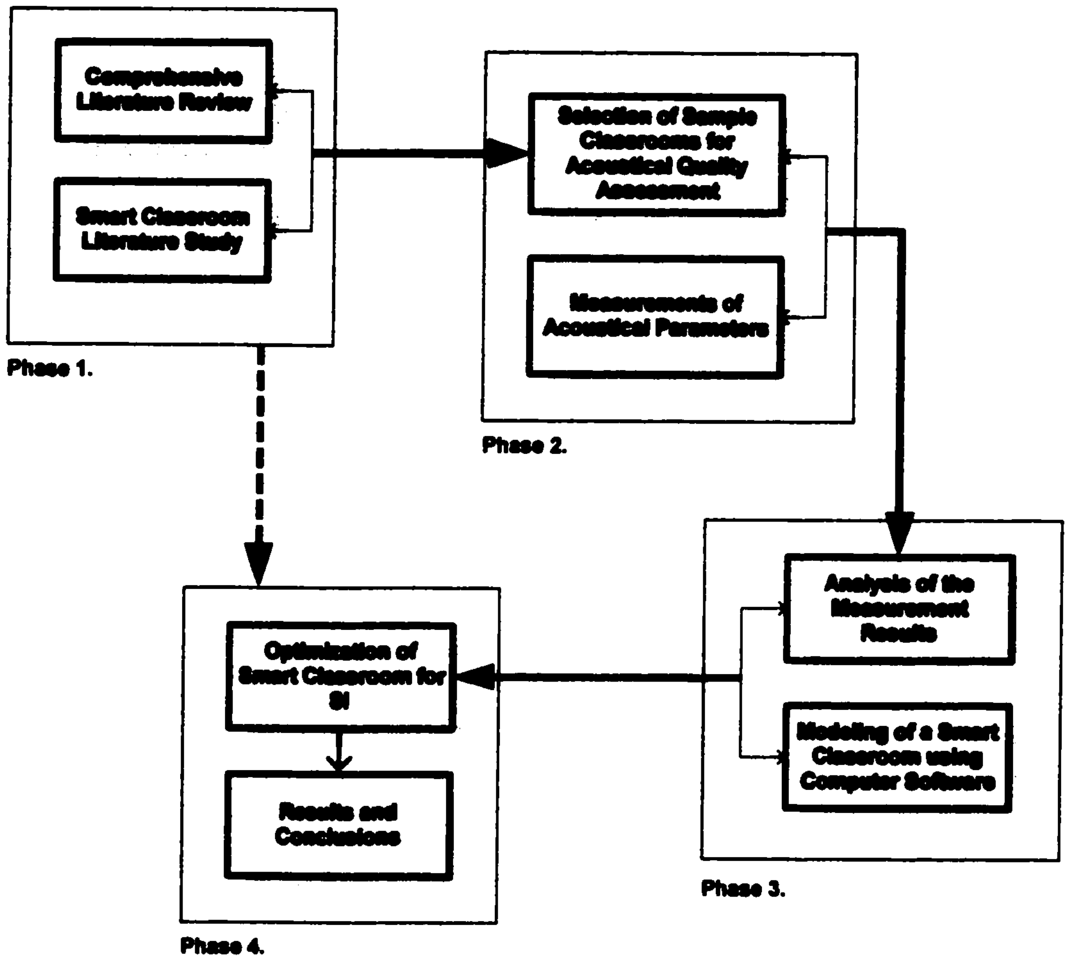


Figure 1.1. Flow chart showing the various steps and phases of the research work.

1.5 Scope and Limitations

The scope of the study extends to identification of the best material configuration of an ideal smart classroom and optimal material assignment with diverse absorption potentials at different frequencies. The model developed is evaluated in terms of varying its sound absorption characteristics and speech intelligibility. However, the technical and electronic aspects of smart classroom are not simulated in this study. The model developed is simple rectangular classroom geometry with the simplest layout of student workstations. This is to mimic a basic conventional university classroom configuration, which can be converted into a computer classroom as and when required and does not cover the evaluation of an optimum classroom geometry for such applications.

CHAPTER 2

2.0 LITERATURE REVIEW

2.1 Background

For a long time, classrooms have been used for learning, with vocal communication as the basic means of knowledge exchange. This highlights two aspects necessary for good learning within the classroom namely the room enclosure and the sound signals from the instructor. The instructor or speaker sound level varies from person to person and is difficult to control. At times, the teacher is forced to increase the level of his speech, which is quite exhausting and discourages the teacher's willingness to dialogue with the students. The other option that is the classroom enclosure can be looked at and modified or designed such that the teacher's sound is well received and understood by all the students seated in all possible locations and vice versa.

In order to achieve good acoustical conditions within the classroom, the behavior of sound in that space has to be analyzed for speech intelligibility. To accurately predict levels of speech intelligibility, various acoustical indicators have been devised that provide a better understanding of speech sound characteristics within the classroom. This chapter reports the state-of-the-art, conventional and contemporary objective room acoustical indicators in use for evaluation of sound intelligibility in enclosures.

Other issues that need to be addressed are the needs and configuration of modern classrooms. With developing information technology and computer science, it has become necessary to update the conventional classrooms to fulfill the modern education requirements.

As in all other spaces, computers are finding place in classrooms, enhancing the learning and representation process giving rise to a new classification of modern classroom referred to as 'smart classrooms'. This emerging classroom technology is becoming a necessity for universities all around the world. Again it is important to optimize these modern classrooms in terms of speech intelligibility and acoustical properties, which is the main objective of this research. This chapter will also report the basic characteristics and configurations of the smart classrooms.

2.2 Speech Intelligibility (SI) Indicators

Poor classroom acoustics represent a barrier for students, often making it difficult to distinguish a student's own learning deficiency or from difficulties caused by unacceptable classroom acoustics. To overcome this problem, significant research is being carried out in this area, which includes experimental and documentation work, with emphasis on developing objective criteria for speech intelligibility.

The concept of SI came into the picture with the evolution of telecommunication technology systems. Contributions made by French & Stienberg [2] and later by Kryter in developing a subjective measure of speech intelligibility known as the "Articulation Index" (AI). A subjective measure of SI, AI is calculated from the score of a group of experienced listeners with normal hearing who write sentences, words or syllables read to them from selected lists [3,4]. A ratio of clearly read words represents the percentage intelligibility scored from 0 to 1.

This subjective rating heavily depends on the type of speech information being imparted. Figure 2.1 compares the AI to various types of speech signals providing a useful set of intelligibility curves. The curves suggest a low intelligibility rating when the subject understands fewer words and as the AI score is higher, the intelligibility rating also increases.

Peutz [3] further emphasized the validity of AI by detailing the procedure to calculate the articulation loss of consonants ($\%AL_{cons}$), thus separating the subjective analysis of vowels and consonants. These studies also highlighted the subjective characteristics of articulation of the speaker and hearing acuity with respect to speech of the listener [3]. $\%AL_{cons}$ is evaluated by the following equations:

$$AL_{cons} = \left(\frac{200D^2T^2}{V} + a\right) \qquad \% \text{ for } D \le D_c$$

$$AL_{cons} = (9T + a) \qquad \% \text{ for } D > D_c$$

where, $D_c = 0.2\sqrt{V/T}, .m$

T= reverberation time (at 1400 Hz), in seconds,

V= volume of the room, m^3

D= distance of source to listener, m

a= constant for good listener varying from 1.5 to 12.5%

Optimum rating and tolerance can be assessed based on the following range of percentage values [3,12]:

{<10% = Very Good}

{>10%<15% = Good}

{>15% = Insufficient}

A subjective measure of SI, AI is calculated from the score of a group of experienced listeners with normal hearing who write sentences, words or syllables read to them from selected lists [4]. A ratio of clearly read words represents the percentage intelligibility scored from 0 to 1. Experiments show a decrease in intelligibility rating with an increase in the distance from the sound source until a critical distance D_c is reached beyond which the intelligibility is independent of the distance between the source and the listener [3]. Since consonants are more vulnerable to reverberation than vowels, $\%AL_{cons}$ is a better SI indicator than AI. The critical distance D_c is given by:

$$D_c = 0.2\sqrt{V/T}, \quad m$$

The most important and well-documented acoustical measure is the "Reverberation Time" (RT), which is used to determine how quickly sound decays in a room [6]. Reverberation (R) as a basic measure of architectural acoustics was the result of pioneering work by W.C. Sabine [7]. The relationships between SI and RT has been very well studied resulting in the development of standards specifying the range of RT necessary for Speech Intelligibility for various spaces. Reverberation Time depends upon the physical volume and the surface materials of the room.

The most commonly used formula for predicting RT are the Sabine and Eyring formulae. Both these formulae are based on the assumption of a diffused sound field [8]. It can be determined as follows:

$$RT = 0.161 * \frac{V}{Sa_{sab}}$$

where, V = Volume, m^3

$S = \sum_i S_i$ = Surface area of the enclosure, m^2

$a_{sab} = \bar{\alpha}$, the average absorption coefficient $\bar{\alpha}$, given by [8],

$$\bar{\alpha} = \frac{1}{S}\sum_i \alpha_i S_i$$

The Eyring equation is more complex but avoids the inaccuracy of the Sabine equation arising in the case of rooms with perfect & complete absorption. However the Sabine equation as described earlier is the most commonly used. The Eyring equation is as follows:

where, $$RT = 0.163\frac{V}{Sa_{Eyr.}} \qquad a_{Eyr.} = -Ln(1-\overline{\alpha})$$

The reverberation time is commonly given by slope of the best fit straight line to sound level decay curve from –5 to –25 or –30 (RT_{25}) or –35 dB (RT_{30}), extrapolated to –60 dB. For classrooms and speech related spaces, the ideal reverberation time ranges from 0.5s to 0.9s for elementary classrooms while it ranges from 0.6 seconds (sec) to 1.3 sec for lecture and conference rooms as shown in Figure 2.2, which depicts the optimum RT range for educational facilities.

The pioneering work of Hass [9] led to the observation that reverberation affects Speech Intelligibility by affecting the early and late arriving sound energies and, more importantly, their ratio that is the early and late energy fraction [9,11]. The early and late sound energies are usually defined as the total speech energy radiated by the speech source which arrives at the receiver position at times greater than and less than about 50 msec respectively after the arrival of the direct sound. SI is directly related to the early-to-late arriving energy fraction with excessive reverberation resulting in reduced ratio of the early-to-late energy and therefore, in lower SI [12].

Reverberation can be quantified by a number of measures besides the early-to-late arriving energy fractions including RT and Early decay time

(EDT), given by the slope of best fit straight line to sound level decay curve from 0 to -10 dB, extrapolated to -60 dB.

The combined effect of early arriving sound reflections and the direct sound increases the intelligibility of speech making the direct sound seem louder and crisper, while the later arriving reflections degrade the SI causing the speech sound to blur into the next one. The ratio of the early arriving to later arriving sound has been used as an indicator of the effect of room acoustics in the clarity and intelligibility of speech [12], thus formulating another indicator referred to as Clarity (C_{50}) measured at 50 msec after the direct sound as the effects of both direct sound & reflected sound on SI in rooms can be correctly assessed within 50 msec after the direct sound [10]. Clarity is defined as:

$$C_{50} = 10\log\left\{ \int_{0}^{50ms} P^2(t)\ dt \Big/ \int_{50ms}^{\infty} P^2(t)\ dt \right\} \qquad ,dB$$

Where *P(t)* is the instantaneous sound pressure determined from the room impulse response.

For C_{50}, its value ranges from –6.4 to 1.0 bB with 0.0 as the ideal situation [13].

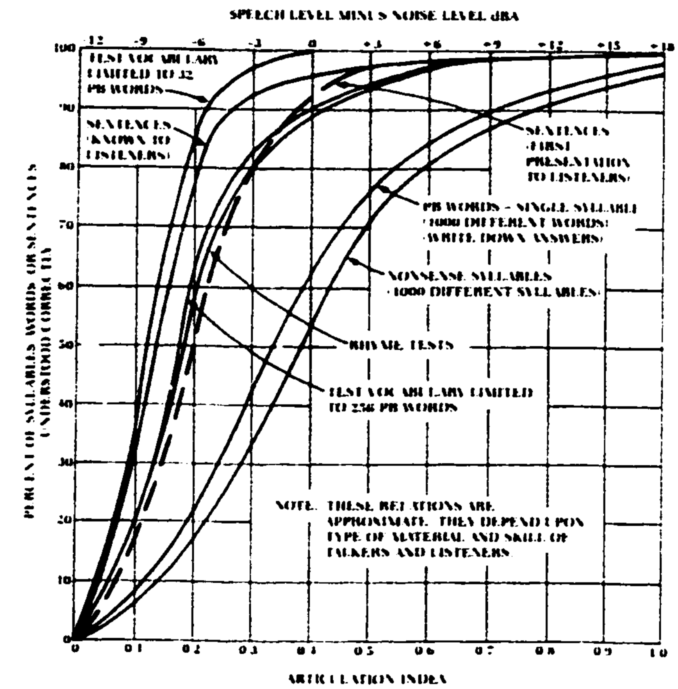


Figure 2.1. *Intelligibility curves. Relationship between articulation index and various measures of speech intelligibility and signal to noise ratio (A-weighted) [Adapted from [51]]*

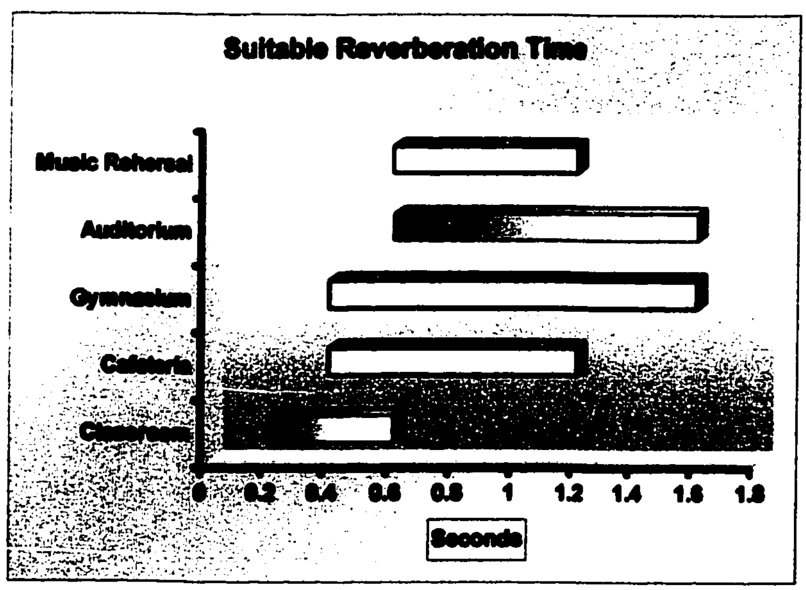


Figure 2.2. *Suitable RT for various rooms typically found in education facilities {redrawn from [1]}.*

Another indicator referred to as Deutlichkeit or Definition (D_{50}) is a ratio of early arriving sound energy to the total sound energy given by the below mentioned equation with its value ranges from 0.4 to 0.6. [13]:

$$D_{50} = \int_0^{50ms} P^2(t)\ dt \Bigg/ \int_0^{\infty} P^2(t)\ dt \qquad ,ratio$$

Although the two measures are related mathematically, recent studies indicate that C_{50} is better because it is linearly related to subjective assessment of clarity of speech sound [12,14]. The studies by Locher & Burger showed that the reverberation time gives insufficient indication of SI [15]. The Signal to Noise ratio (S/N) devised by them proved to be a more effective predictor. This ratio is equal to the level of speech minus the level of background noise, both at listener position. The speech level is the speaker's direct sound level also depending on the speaker & listener distance [11]. In general, the S/N ratio in classrooms is sufficient for speech intelligibility if it is between +10 to +15 dB. The extension of this theory resulted in modified signal to noise ratio (SNR_{95}) that was based on the best fitting correlation with SI, taking into account the effect of fluctuating ambient background noise on SI [16]. However, this predictor is less used for SI evaluation in rooms due to its complex nature and the least impact of fluctuating background noise on SI in rooms.

$$SNR_{95} = \int_{0}^{95ms} a(t)\ P^2\ (t)\ dt \Big/ \int_{95ms}^{\infty} P^2\ (t)\ dt \qquad ,dB$$

Where P(t) is the instantaneous pressure in the room impulse response and a(t) is a weighing factor. SNR_{95} value ranges from -6 to +6 at 1KHz [13].

Another indicator which is the result of a combination of S/N and the room acoustical characteristics is referred to as useful-to-detrimental ratio (U_{50}), which is measured by adding an S/N component to the early to late arriving sound ratio concept. U_{50} sound ratio is defined as the logarithmic ratio of the useful to detrimental sound energies [10,12,13]. With the useful sound being the early arriving sound energy while the detrimental sound is the sum of the late arriving speech energy and the ambient noise. U_{50} is defined simply, for 50 ms early time limit (for classrooms) as stated below and its value ranges from -5.6 to 1.0 [13].

$$U_{50} = 10 \cdot Log\left\{\frac{E}{L+N}\right\} \qquad ,dB$$

Where, E = early arriving speech energy,

L = Late arriving speech energy,

N = ambient noise energy.

With the combination of C_{50} and the availability of steady state speech and noise levels, U_{50} values can be calculated by [12,21]:

$$U_{50} = 10.Log\left\{\frac{E/L_{50}}{1+(E/L_{50}+1)N/S}\right\} \qquad ,dB$$

Where S = speech energy,

E/L_{50} = linear early-to-late arriving sound ratio

$C_{50} = 10Log(E/L_{50})$

Thus the signal to noise ratio and its derivatives appears to correlate very well with measured speech intelligibility and takes into account the reflection sequence of sound energy as well as background noise in the calculation procedure [17].

A Speech Transmission Index (STI), proposed by Steeneken and Houtgast [18,23]. STI is based on the concept of the Modulation Transfer Function (MTF) which was originally introduced by Schroeder [19]. The MTF defined the impulse spectrum to be a stationary zero mean at the beginning, that is the ambient noise signal with the total sound energy being the integration of squared amplitude of the total spectrum. The squared output neglects the phase and considers only the magnitude obtained by the ordinary transfer function.

The STI is based on the MTF, with an assumption that the degradation of SI in a room is related to reduction of the amplitude modulation of speech signals by both room acoustics and ambient noise. The reduction in amplitude modulation is assessed for 98 combinations of 7 acoustical octave bands and

14 modulation frequencies bands. These are then reduced to single number STI just like AI discussed earlier [20,21].

STI ratio is derived from [13],

$$m(F)=\left\{\int_0^\infty P^2(t)*e^{f(2\pi F)}dt \Big/ \int_0^\infty P^2(t)\ dt\right\}$$

Where, F = modulation frequency, Hz and f = the frequency of sound signal

For diffused sound conditions:

$$m(F)=\frac{1}{\sqrt{1+\left(2\pi F*(T/13.8)^2\right)}}*\frac{1}{1+10^{(-S/N)/10}}$$

STI is rated between 0 and 1, with:

0	< STI ≤ 0.32	= bad
0.32	≤ STI ≤ 0.45	= poor
0.45	≤ STI ≤ 0.60	= fair
0.60	≤ STI ≤ 0.75	= good
0.75	≤ STI ≤ 1.0	= excellent

The STI is the most complex intelligibility measurement technique currently available and has found place among accurate measurement predictors of SI. It is only the advent of modern microprocessor and desktop computer technology that have enabled this technique to be implemented on a practical basis. The STI intelligibility measurement technique automatically takes both background noise and RT into account. For the purpose of fast evaluation of Speech Intelligibility, a simplified version of the STI method is used to replace the lengthy calculations involved with STI. This measure is termed as the Rapid STI or RASTI". It is based on only 9 measured modulation reductions obtained in only the 500 and 2 kHz octave bands. RASTI is given by [13]:

$$RASTI = \left[\left(\overline{S/N}\right)_{app} + 5\right]./30$$

$$(S/N)_{app} = 10.Log\left[m(F)/(1-m(F))\right] \qquad ,dB$$

$$\text{Where } \left(-15 \le (S/N)_{app} \le +15\right)$$

The acoustical predictors described are the results of research and experimental studies mostly highlighting the SI aspects in enclosures. Although various other indicators for objective assessment of acoustical conditions exist, the ones described extensively represent the acoustical characteristics of spaces used for speech such as classrooms and lecture halls.

2.3 Background Noise (BN)

Background noise in a classroom includes sound from outdoors, building services and utilities operating in the building at their maximum efficiency, but excludes the noise generated by people within the enclosure or sound generated by temporary equipment. High ambient noise or BN from mechanical equipment such as HVAC systems, electronic equipment and lighting fixtures are most common in existing classrooms. The presence of high BN in a classroom is highly detrimental to SI and results in reduction of signal to noise ratio. To achieve the required S/N ratio of at least 10 dB for minimal reception of sound, the instructor has to raise his voice causing vocal strain.

The effect of BN on acoustics of an enclosure has been studied in detail and various noise-rating indices have been derived to evaluate the occupant acceptability of indoor BN. These include the traditional A-weighted sound pressure level (dB-A), Noise Criteria (NC), the most recent Room Criteria (RC) and the new RC Mark II. Each sound rating method is developed based on data for specific applications [58]. The A-weighted sound level is a single number measure of the relative loudness of noise, which is extensively used to classify noise in rooms. The rating is expressed as a number followed by dB-A. The maximum one hour A-weighted steady state BN of 35 db-A for learning spaces with a volume less than 566 m3 is recommended by the ANSI standard on classroom acoustics, thus highlighting the contemporary application of dB-A rating.

The NC method is widely used and is a single number rating that is somewhat sensitive to the relative loudness and speech interference properties of a given noise spectrum. The method consists of a family of criterion curves extending from 63 Hz to 8 kHz and a tangency rating procedure [58]. The criterion curves define the limits of octave band spectra that must be exceeded to meet occupant acceptability in certain spaces. The rating is expressed as NC followed by a number, which describes the level. For classrooms the NC rating of NC-25 to NC-35 has been found to be optimum, achieving a better S/N ratio [59].

The RC method consists of criterion curves and rating procedure, which differs from NC curves achieving a well-balanced bland-sound spectrum, and two additional octave bands (16 and 31 Hz) are added to include possible excessive low-frequency noise. This rating procedure assesses BN in spaces both on the basis of its effect on speech communication and a subjective sound quality. The rating is expressed as RC followed by a number to show the level of the noise and a letter to indicate the quality such as RC 35(N) is the maximum allowable RC rating for classrooms where 'N' denotes neutral characteristics.

ASHRAE sponsored research resulted in the most recent rating known as RC Mark II, an enhancement of the RC rating. This method is used as a diagnostic tool for analysis of noise problems in rooms utilizing a family of criterion curves, a procedure for determining the RC numerical rating and the noise spectral quality and finally a procedure for estimation of occupant satisfaction depending upon the spectrum shape (Quality Assessment Index) [58]. The quality assessment index is useful in estimating the probable reaction of an occupant to the existing noise in the enclosure.

The noise rating procedures described above are efficient tools that define the noise characteristics in rooms. Depending upon the functional aspects of an enclosure, recommended noise rating ranges have been evolved that best suit the specific activities. The ratings are also used to evaluate the noise in existing rooms and identify noise spectrum related problems.

2.4 Comparison of Speech Intelligibility Indicators

The objective indicators of speech intelligibility devised, modified and applied for characterizing the room acoustical conditions vary in the overall concept but relationships between them can be established. Many studies were carried out comparing the speech intelligibility predictors for their accuracy to represent the actual acoustical conditions of the room.

These indicators are RT, EDT, C_{50}, D_{50}, S/N, U_{50} and STI. Due to the dependence of SI on the speech level, ambient noise and the room physical characteristics, it is necessary to investigate two of these predictors. The RT and the S/N describe the physical as well as the ambient acoustical conditions of the room. Studies have been carried out to evaluate the combination of the other indicators with these basic sound measures to accurately predict speech intelligibility.

A study by K. D. Jakob [24] described a comparison between the intelligibility ratings obtained by the MT method, which is basically the STI concept, S/N and $\%Al_{cons}$ and found that the least error or deviation was measured using the MT method while $\%Al_{cons}$ had the highest deviation. Similar research by Bradley [9,21] concluded that the STI is an accurate method for predicting speech intelligibility.

A study of SI in classrooms by Bradley [14] measured all predictors and concluded that the union of RT, S/N and STI gave the best results in terms of representing the acoustic measures of the room for good speech. The results from the other indicators of speech intelligibility were quite similar to the STI method but the closest to actual conditions was STI.

In another research, Bradley and Bistafa [25] and also Reich and Bradley [26], classrooms were studied and simulated, again highlighting the authenticity of STI in terms of its accuracy along with RT and S/N measurements in representing the realistic classroom acoustical conditions. The correlations of these predictors were also verified in another study [27]. Other authors in their respective studies have described the same findings and have extensively used these predictors in their studies to evaluate SI in rooms [11,22].

Objective acoustical parameters RT, EDT, C, D, L and RASTI were measured in churches for speech intelligibility in Portugal [28]. Thirty-six churches were surveyed and analyzed for speech intelligibility. The conclusion was that the RASTI (a simpler version of STI) method predicted speech intelligibility very well.

The earlier studies described above confirmed the authenticity of the STI measurements in representing the speech Intelligibility parameters along with the RT and the speech energy to ambient noise ratio S/N measurements. The analysis of these sound indicators enables one to define the acoustical conditions of the classroom and in turn can be used to optimize the classroom for SI.

2.5 Computer Classrooms for Active Learning

Present day university students spend most of their time working with technology, most of which is computer based. A survey of universities conducted in 1999 [29] found that campuses where faculty have a ready access to computers in classrooms see a dramatic increase in classroom use of instructional materials obtained from the world wide web. The web has become a popular and efficient mode of education and research. Universities with more computers available in classrooms are more likely to see advanced uses of computers for instruction. Evidence suggests that the longer the faculty use computers in classrooms, the more likely they are to use advanced computer applications that are most closely tied to the curriculum.

A separate study in 1996 [29] found that in universities where the Internet has been used for education, student performance improved. Results showed significant higher scores on measurements of communication, presentation of ideas and information management for experimental groups with online access than that of the control group with no online access.

The introduction of computers in classrooms support interactive and collaborative learning, facilitating a shift from disclosing information to processing information, with improved presentation and dialog. The result is a considerable change in the teaching and learning process within the classroom environment. Interaction between instructor and students, among students and between all the participants is enhanced with user-friendly technology, which inspires presenters who rely on improvisation, spontaneity and audience participation.

The conventional classrooms are thus changing to modern computer interactive rooms for learning referred to as "smart classrooms". Instead of being isolated units, these smart classrooms are interconnected with access to stored resources and live video connections. The computers are networked to local area network, a campus network and Internet, providing access to a wide range of resources [30]. Computers at each student workstation in classrooms create a collaborative learning environment with the instructor as a mentor, making classroom technology as simple and non-intimidating as possible. Figure 2.3 shows interior views of some computer-assisted classrooms while Figure 2.4 illustrates different configurations of university smart classrooms. Different teaching styles, that is simulation, investigation, proper discussions, collaborative discovery learning, software demonstrations etc. can be well instructed using smart classrooms.

The computer classrooms or smart classrooms and computer labs share some characteristics and capabilities, but there are important differences. In a smart classroom, an instructor and students have access to presentation capabilities for group instruction, while the computer lab is where students come to work individually. The faculty in a smart classroom can display a student's work on a large screen, can use a console to monitor a student's progress, identify common problems and share solutions with the class [29]. In addition, presenters can blank all screens for full attention along with screen sharing. Any participant can share a document and when the session is over; documents created can be saved and kept for reference by any participant. Some of the additional components of smart classrooms, which make them different from conventional classrooms, are [30]:

a. Computer work stations for each student
b. White board/electronic interactive white board
c. Wide screens for display
d. Control panels for VCR and video projector
e. Presenter's or instructor's work station/lectern
f. Video data projector/overhead projector/slide projector
g. Sound reinforcement system (if needed)

Two types of interactive computer classrooms are used in universities. These are as follows:

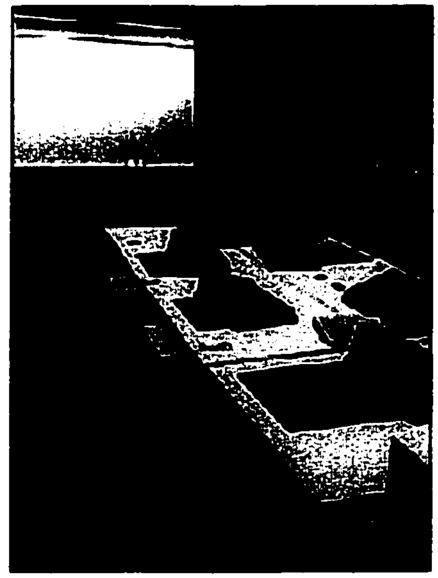
a. Smart Presentation Computer classrooms
b. Smart Interactive Computer Classrooms

Smart presentation computer classrooms are equipped for computer presentation capabilities at the front of the room and include a small fixed lectern with a connection for a laptop computer or an installed desk top computer for the presenter; a ceiling-mounted video/data projector; two screens; two ceiling-mounted speakers; a VCR, and a media cabinet that houses other networking equipment. Faculty may bring a laptop computer with their choice of platform, loaded with necessary configuration and applications or can use a computer installed in the classroom. Data connectivity provides access to information outside the classroom.

Smart interactive computer classrooms are equipped with computers at each student station. These interactive multi-media classrooms include a teacher's computer, a master control unit for the teacher in front of the room and networked student laptop or desktop computers. Features the faculty find desirable in the interactive classroom are the ability to display information from the presenter's computer to a large screen, the ability to display information from any student work station, send selected data to every computer screen in the room and use the student computers as a response pad for presenters questions.

As described above, the smart classroom is much more complicated than the conventional classrooms both in terms of its functional as well as visual and communicational aspects. Additional noise sources are distributed throughout the classroom like data display equipment, power sources, UPS system etc. that add up to the existing background noise in classrooms. Smart classrooms highly improve the visual and technological learning capabilities but the smartness of these classrooms would be lost if not acoustically optimized for SI.

(b)

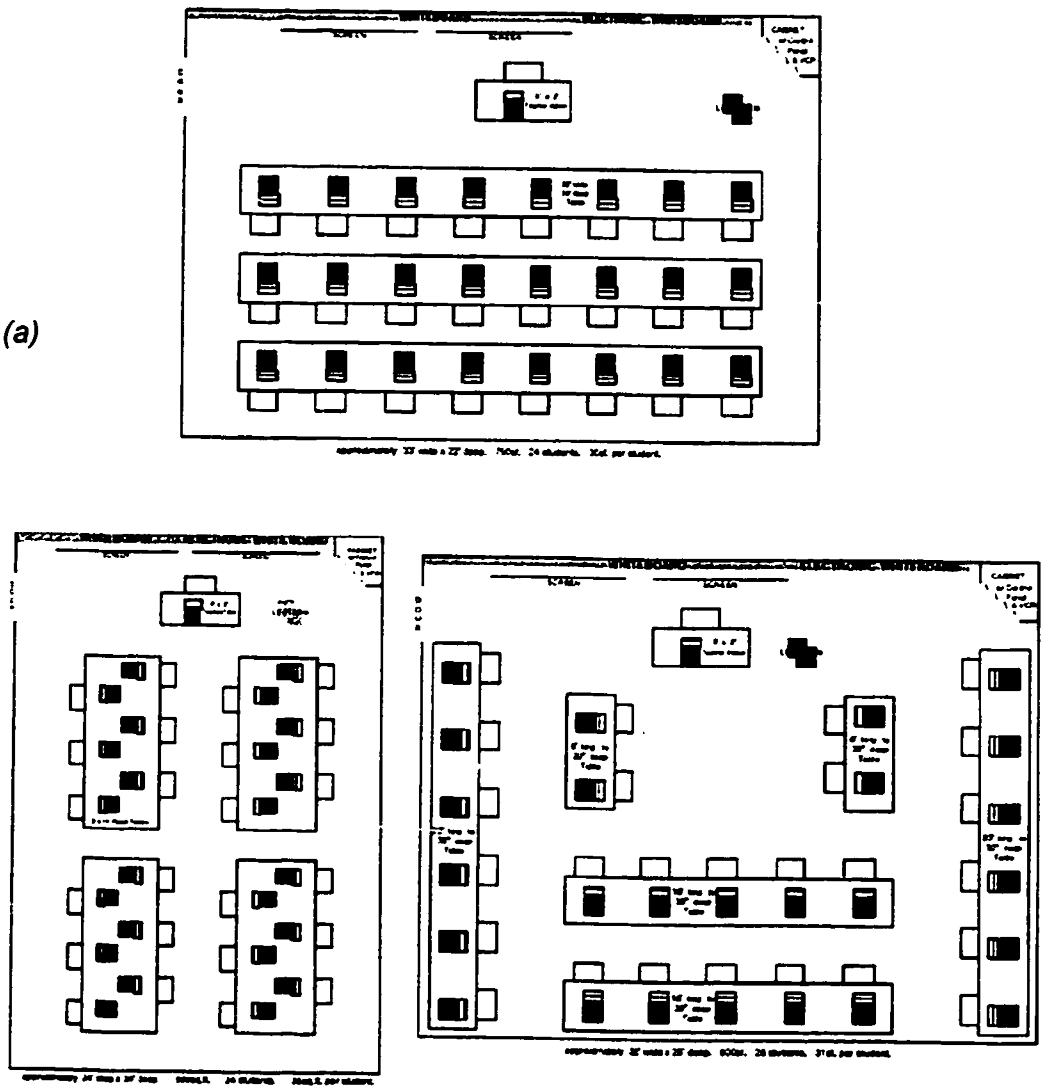


(a)

(c)

Figure 2.3 (a, b, c). ***Smart University Classrooms [30], showing the integration of computers in classrooms for better learning.***

(a)



(b) (c)

Figure 2.4 (a, b, C). Layouts of some Smart University Classrooms in plan [30].

2.6 Room Acoustics, Modeling and Simulation Software

2.6.1 Background

About 30 years ago, a major revolution in the field of Acoustics took place with the introduction of computer technology and digital electronics. In 1968 the famous paper by Stram, Krokstad and Sorsdal [31] on computer simulation in room acoustics was published, which highlighted the algorithms generated into a computer language to facilitate acoustical calculation of rooms. Since then various programs have been developed which are used for the purpose of research, training and consultancy practices.

Before the development of simulation software, scale models were used to predict and calculate the acoustical characteristics of rooms and other spaces. Miniature models of the space were visualized using small microphones, the results of which were usually biased due to the actual room/material properties and source characteristics. Therefore software developed to simulate room acoustics has become an efficient tool for acoustical consultants and researchers to predict the sound quality within an enclosure.

2.6.2 Advantages of Computer Modeling

The acoustical models generated through the computer software are much more flexible as compared to the scale models used earlier. Once the room is modeled, it is easy to modify the geometry of the design and also use a wide variety of materials with different absorption coefficient as required. The computer models are fast as, typically, new sets of results are available a few hours after some changes to the model have been proposed [32]. With the improvement of both computer hardware and software technology, the speed and accuracy of calculations have further improved. However, the advantages are not restricted to time and cost only. Using computer models, the result can be visualized and analyzed much better than before with more detailed information about the room acoustical characteristics. Thus as the complexity of spatial and environmental requirements keep on increasing, it is essential to control the same using efficient simulation software that allows us to visualize the enclosure close to reality.

2.6.3 Simulation of Sound in Rooms

With the large-scale development in acoustical computer models, highly accurate simulation of room acoustics is possible with reduced calculation time. The modeling software uses the principles of sound propagation in relation to the architectural environment. These room acoustical models have an advantage over the scaled models as described earlier and have been reliable and efficient design tools in the field of acoustics. The simulations can be calculated and viewed not only visually but audibly using the auralisation techniques.

2.6.4 Basic Modeling Principles

In architectural acoustics, the propagation of sound is described by sound particles moving in the form of sound rays. The geometric models thus generated give a better picture of the varied frequency related properties of a space along with the geometrical complexities of the enclosure. Both high and low frequency dominated sound plays a role in architectural spaces with the principle of sound rays accounting for the effect of all octave band frequency ranges.

For the simulation of sound in rooms, there are two classic geometrical methods, namely the Ray Tracing Method and the Imaging Tracing Method [32,33]. Both the methods use ray based sound geometry to create multiple reflections, which gives an exaggerated view of the actual characteristics of sound waves. Here the sound wave features such as frequency dictated wavelength characteristics should also be accommodated. The ray based geometrical model can very well define the initial reflections of sound rays where most of the sound energy is reflected while in the latter reflections the diffusion of sound plays a major role. One way of introducing the wave nature of sound into geometrical models is by assigning a scattering coefficient to each surface [33]. This would allow the diffusion behavior of a specular sound ray to be modeled creating reliable results. Figure 2.5, shows the combination of the modeling techniques to improve efficiency of the acoustical simulation.

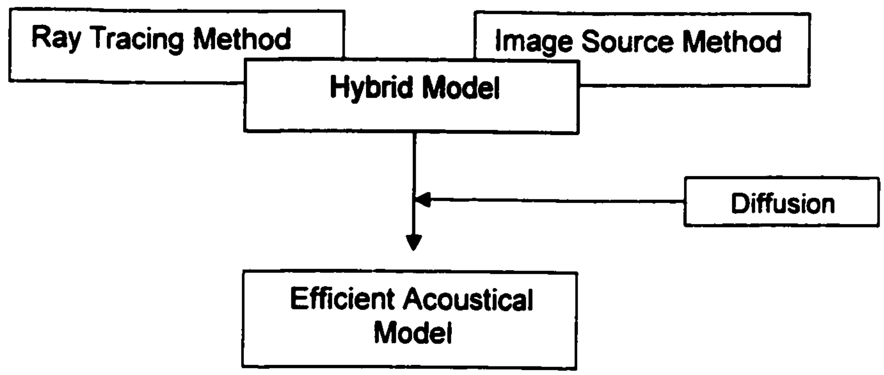


Figure 2.5. Combination of modeling techniques.

Depending upon the time related reflections within an enclosure, the reflections can be classified in three stages i.e., Direct Sound, Early Reflections (first order) and the Late Reflections (second order). Figure 2.6, presents a simplified room geometry and propagation path of direct sound and some early reflections [34]. An impulse response of a concert hall is shown in Figure 2.7, clearly reflecting the effects of diffused elements in sound propagation.

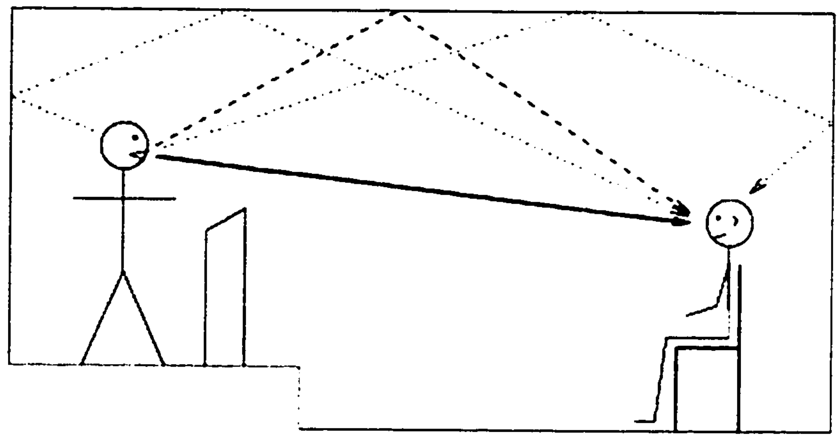


Figure 2.6. Simple room geometry & visualization of the direct sound (solid line), first order reflection (dashed line) and second order reflection (dotted line).

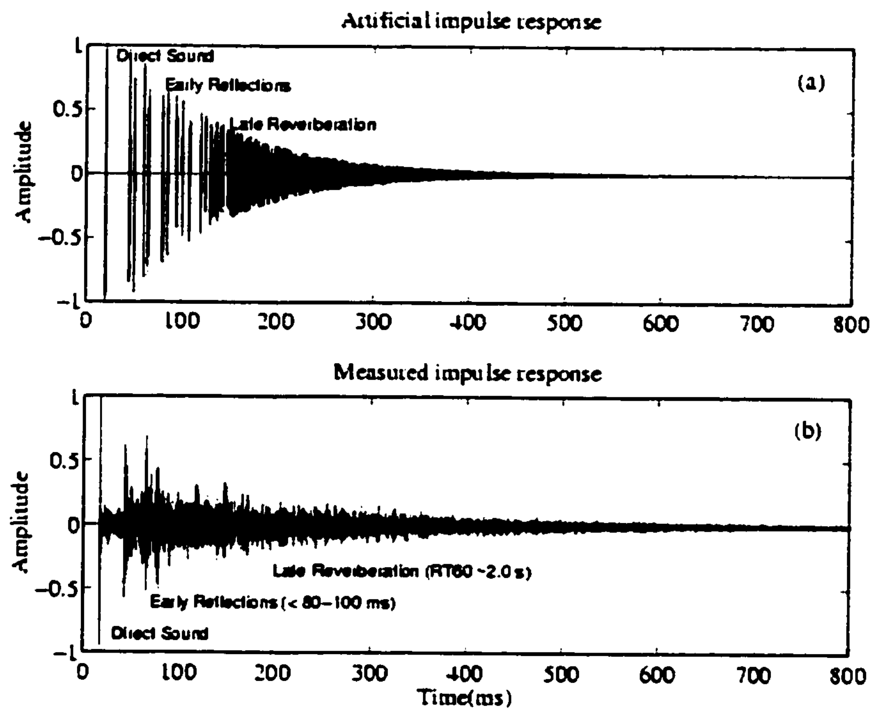


Figure 2.7. (a) Room response simulation. The response is typically considered to consist of three parts: direct sound, early reflection and late reverberation. The sound field is diffused in the late reverberation part. (b) A measured response of a concert hall. Notice the reverberation tail in both cases with the effect of diffusion evident in the measured impulse.

2.6.5 Ray Tracing Method (RTM)

The Ray tracing method is based on the propagation of sound waves in the form of a sound ray emitted in various directions from a sound source. With each reflection of the sound ray, energy is lost in accordance to the absorption coefficient of the surface it hits, with the new direction of propagation determined by Snell's law of optical geometry [33]. Such reflections are referred to as 'specular reflections'. To model the geometric sound rays, an area of influence of the sound source in terms of area or volume has to be defined. The same area can be considered as a cone or pyramid with the sound source as its axis. Therefore if a sound source hits a surface with an area 'A' after having traveled the time 't' with the area of the wave front per ray not larger than A/2, the minimum number of rays 'N' can be given by [32]:

$$N \geq \frac{8 \pi c^2}{A} t^2$$

Where 'c' is the speed of sound in air.

Thus, a large number of sound rays are generated for a typical room. For example if the minimum surface area is 10 M^2 and the propagation time is only 600 ms, at least 100,000 rays will be generated. Initially circular cones were used to direct the sound rays but lately triangular pyramids have been used to overcome the overlapping cones. Figure 2.8 presents a model of a concert hall using Odeon 5.0, with direct sound and all the first and second order reflection paths obtained by ray tracing techniques. The geometrical model of the hall contains 300 polygons and 40,000 rays were emitted uniformly over a sphere [34].

2.6.6 Image Source Method (ISM)

The Image Source Method is also based on specular reflections but is constructed geometrically by mirroring the source in the plane of reflecting surfaces. These reflections are easily calculated in a rectangular room up to a certain order of reflection where the approximate number of reflections within a particular radius is given by [32]:

$$N_{ref} = \frac{4\pi c^3}{3V} t^3$$

Where 'c' is the speed of sound in air, 't' is the time of travel and 'V' is the volume of the room. Thus the average number of reflections increases with time in the third power. This method gives accurate results but for complex enclosures with a large number of complex surfaces, it is difficult to generate sources. With 'n' surfaces there are 'n' possible image source of first and each reflection creating 'n-1' second order image source and so on. Up to reflection order 'i' the number of possible image source 'N_{sou}' will be [32]:

$$N_{sou} = 1 + \frac{n}{n-2}\left((n-1)^i - 1\right) \approx (n-1)^i$$

In case we have a 15,000 m^3 room modeled by 30 surfaces, calculating reflections up to 600 ms, a reflection order 'I = 13' is needed, generating approximately 29^{13} image source. Such a large calculation goes in vain in the case of certain receiver positions as at certain receiver locations most of the image sources do not contribute reflections and are valid only for a specific receiver positions. Therefore this method is used for simpler structures with low order reflections i.e. for non-reverberant enclosures. Figure 2.9 and 2.10 graphically describe the image source method [34].

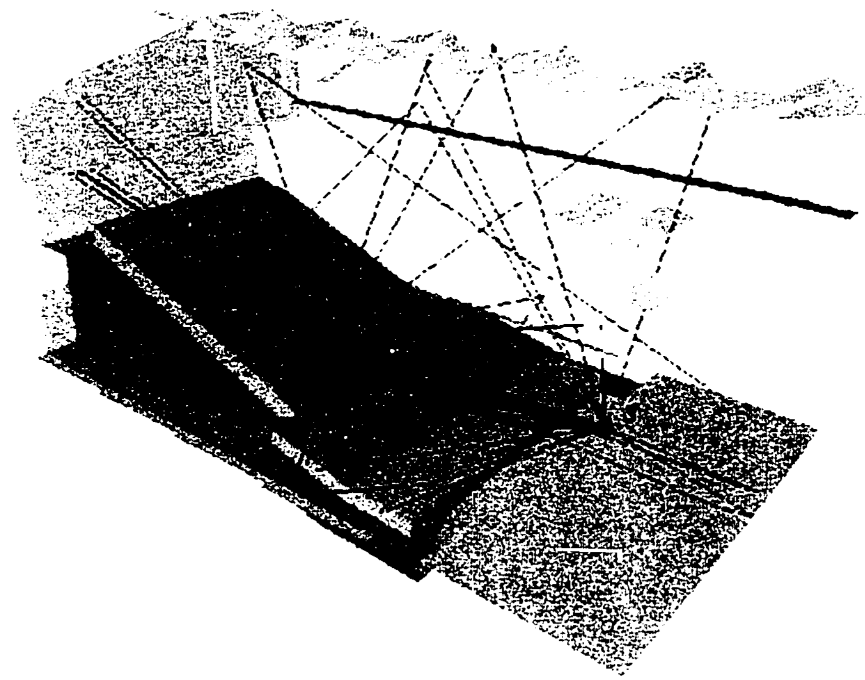


Figure 2.8. The direct sound, first and second order reflection paths in a concert hall obtained by a ray – tracing simulation. S and L denote the source and the listener respectively. (Adapted from [41])

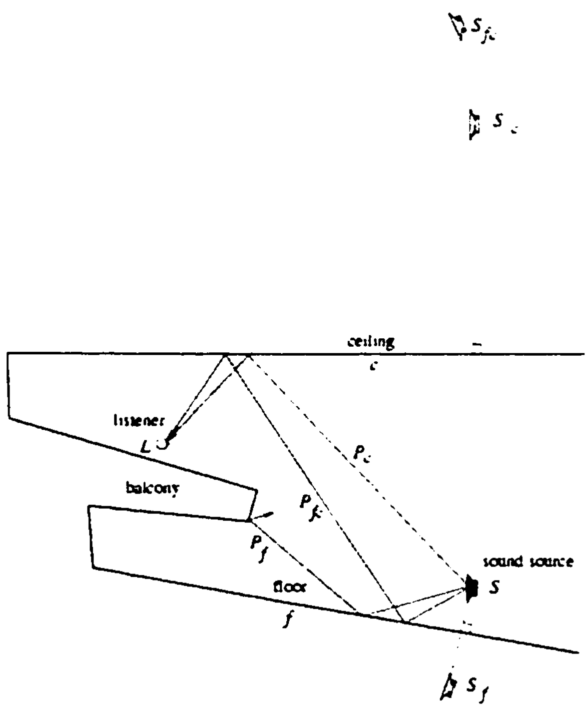


Figure 2.9. The image source method. The sound source is reflected at each surface to produce image sources which represent the corresponding reflection paths. The image source 'S_c' and 'S_{fc}' representing first and second order reflections from the ceiling are visible to the listener 'L' while the reflection from the floor 'P_f' is obscured by the balcony. (Adapted from [34])

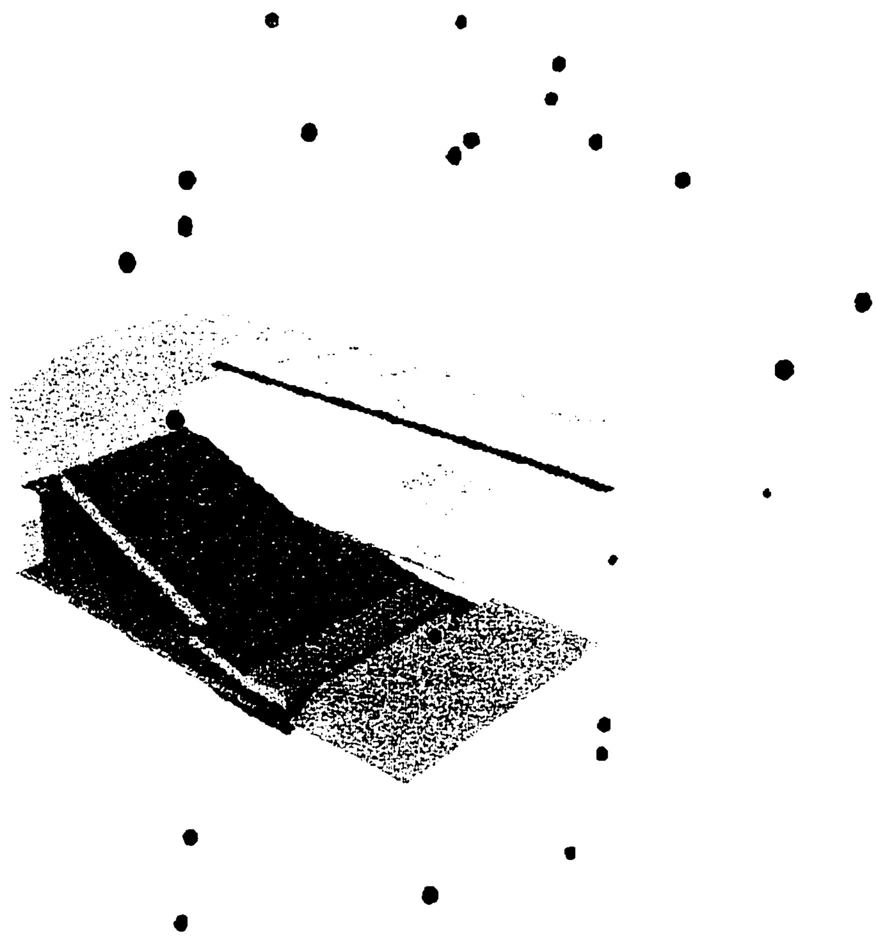


Figure 2.10. ***The computed image source in a concert hall. All the visible first order and second order sources are shown as spheres. 'S' and 'L' denote the source and the listener, respectively (Adapted from [41]).***

2.6.7 The Hybrid Model (HD)

The best features of the earlier described ISM and RTM are combined forming the hybrid method, the idea of which is to find image source by tracing valid rays from the source and noting the surfaces they hit. The sequence of reflections is tested for their contributions at the particular receiver position called as visibility tests, which are performed by tracing back from the receiver towards the image source. Once the back tracking has found an image to be valid, then the level of the corresponding reflection is simply the product of the energy reflection co-efficient of the walls involved and the level of the source in the relevant direction of radiation. The distance to the image source gives the arrival time of reflection [32]. Avoiding duplication of the reflection becomes important as it might cause an error in the reflectogram, thus it is necessary to keep track of the early reflection image by building an image tree.

Another set of issues to be considered here is the rapidly increasing density of reflections and the decreasing relevance of the details of each reflection as the theoretical models tend to deviate more and more from the physical truths with increasing reflection order [33]. Thus another method needs to compensate for the generation of a reverberation tail, known as a secondary source method.

In this method, the principle of ray tracing is used to define the early reflections, with rays treated as carriers of energy rather than geometrical entities. The energy of the secondary source is the number of rays multiplied by the reflection coefficient of the surface involved in the image tree. Each secondary source radiated into a hemisphere as shown in Figure 2.11 [35] with its intensity proportional to the cosine of the angle between the surface normal and vector from the secondary source to the receiver [37]. The time of arrival of a reflection is determined by the sum of the path lengths from the primary source to the secondary source via intermediate reflected surfaces and the distance from the secondary source to the receiver.

The calculation model is illustrated by Figure 2.12. The rays are followed up to a six-reflection order. The first two reflections are specular with both rays finding image source S_1 and S_{12}. Above the second order, each ray generates an independent secondary source situated on the reflecting surfaces. In a simple box shaped room as seen in the figure, the contributions from the source can be easily identified with two image sources and eight secondary sources. The issue now is the number of rays that would define the image source. Recent experiments have shown that only 500 to 1000 rays are sufficient to obtain reliable results in a typical auditorium. Thus, processing the hybrid models can give better results than the basic pure methods and with a much shorter calculation time.

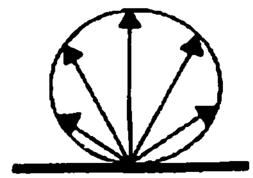


Figure 2.11. *Directivity of secondary source. The directivity is cos2φ, corresponding to the projected area of the surfaces, as seen from a receiver. (Adapted from [32])*

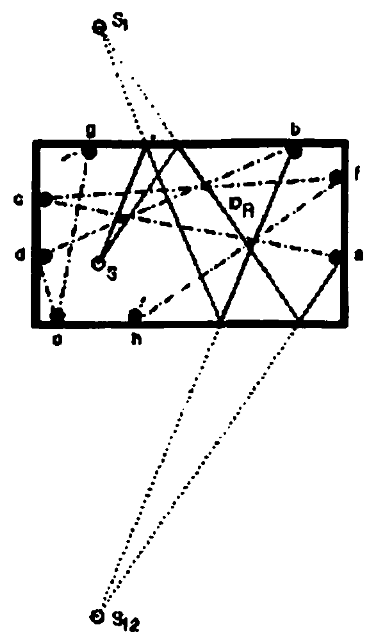


Figure 2.12. *Principle of Hybrid model. The rays create image sources for early reflections and secondary sources on the walls for late reflections. (Adapted from [32])*

2.6.8 Diffusion of Sound

Diffused reflections can be simulated in computer models by statistical methods, with the usage of a scattering coefficient 'S' of a surface in the ratio of reflected sound power in non specular directions and the total reflected sound power [36]. The coefficient may take a value between 0 and 1. 'S = 0' means purely specular reflection, and 'S = 1' is the most ideal diffusivity. The ray reflection with different values of the scattering coefficient is shown in the Figure 2.13. By comparison of computer simulations and measured reverberation time in some cases where absorption coefficient is known, it has been found that the scattering coefficient should normally be set to around 0.1 for large plane surfaces and around 0.7 for highly irregular surfaces. The extreme values of 0 and 1 should be avoided in computer simulations, as they are not realistic. In principle the scattering coefficient varies with frequency; scattering due to the finite size of a surface is most pronounced at low frequencies, whereas scattering due to irregularities of the surface occurs at high frequency [32].

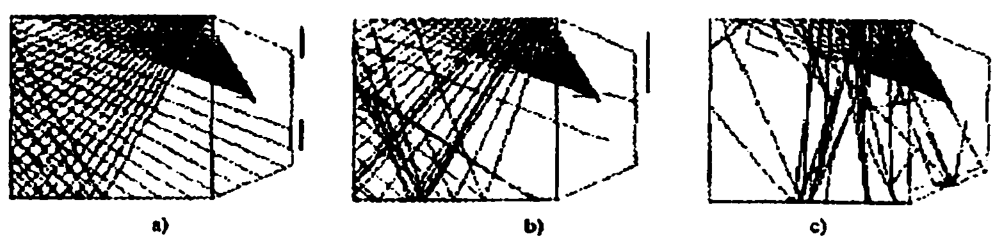


Figure 2.13. Reflections of rays with different scattering coefficients of the surface. a) s = 0; b) s = 0.2; c) s = 1. (Adapted from [32])

2.6.9 Accuracy of Computer Models

In comparison to the measured sound characteristics, the accuracy of the computer models is found to be quite satisfactory. The latest and the best programs, require neither an extensively long calculation time nor extremely detailed room geometry. Computer modeling of room acoustical parameters provides us with realistic simulations of the acoustical environment, the accuracy of which was confirmed in the International round robin where 16 participants, who included researchers and developers of room acoustical simulation software, participated [31]. The results from different software were compared along with the graphical display, images, material descriptions and accuracy. Some of these software depicted accurate results, with most of the software using hybrid models doing better than the pure speculative models. More research and developments in this field will result in 100% accuracy, removing the small percentage of inaccuracy due to the wave nature of sound rays and varied material properties.

2.6.10 Features of ODEON Computer Models

The Reflectogram

The reflectogram displays the arrival of early reflections to a receiver. When the early reflections are calculated from a detected image source, it follows that each single reflection can be separated independently. In addition to arrival time and energy of the reflection, it is also possible to get information about the direction and which surfaces are involved in the reflection path. Figure 2.14 shows a reflectogram of Odeon 5.0. The latter can be very useful if a particular reflection should be removed or modified, e.g. to prevent an echo problem [32].

Reflection Paths

The reflection paths for all early reflections may be visualized in 3D and analyzed in detail as shown in Figure 2.15. During the design of a room it may be interesting to see which surfaces are acting in creating the early reflections. Although it is difficult to extract specific results from such a spatial analysis, it can help to understand how a room responds to sound.

Grid Response Display

With a computer model it is straightforward to calculate the response at large number of receivers distributed in a grid that covers the audience area.

An example is shown in Figure 2.16. It can be extremely useful for acoustic designers to see a mapping of spatial distribution of acoustical parameters. Uneven sound distribution and acoustically weak spots can easily be localized and appropriate countermeasures can be taken.

Auralisation

Using the auralisation technique, a room model is made audible. The concept is that it is possible to listen to sound in a room by the simulation technique using the impulse response from a room model. The auralisation technique offers the possibility to use one's ears and listen to the acoustics of the room already during the design process. Several acoustical problems in a room can easily be detected with the ears, whereas they may be difficult to express with a parameter that can be calculated.

In principle it is possible to use an impulse response measured in a scale model for auralisation. However, the quality may suffer seriously due to transducers. The transducers are one reason that the computer model is superior for auralisation. Another reason is that the information about each reflection's direction of arrival allows a more sophisticated modeling of the listener's head related transfer function.

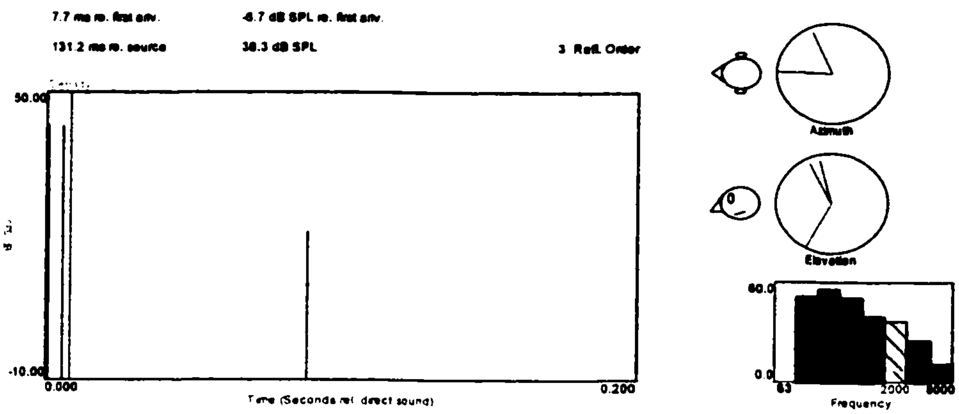


Figure 2.14. The Odeon 5.0 reflectogram. (Adapted from [41])

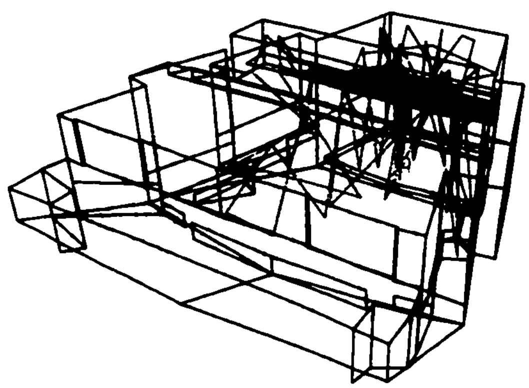


Figure 2.15. Reflection paths of an auditorium represented in 3D (Odeon 5.0) (Adapted from [41])

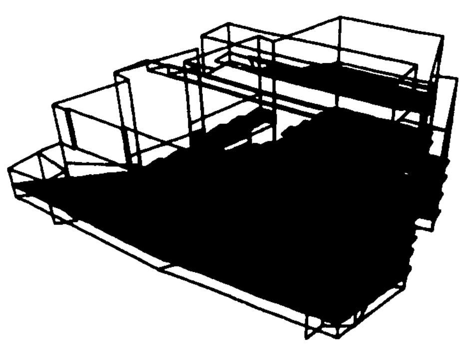


Figure 2.16. Grid response of an auditorium (Odeon 5.0) (Adapted from [41])

2.6.11 ODEON 5.0

Modeling Principles

- Advanced hybrid calculation method taking scattering as well as diffraction into account.
- Two independent methods for the estimation of global reverberation time.

Interactivity and Ease of Use

- 32 bit version for Windows 95, 98 and NT, supporting Windows resources like clip board and printer.
- Multiple Document Interface (MDI), allowing multiple open windows at the same time, e.g. for comparing results.
- Automated calculations allowing calculations of multiple results with most of the parameters set automatically.
- ASCII text result output for use in other applications e.g. spread sheets or Excel.
- Project file management ensures consistency and continuity between sessions.
- Graphical user interface including interactive assignment of material and definition of source and receiver in 3D views.

Optimization and Results

- Parallel calculation in eight octave bands.
- Maps of calculated acoustic energy parameters over receiver surface.
- Point response calculations including parameters like T_{30}, SPL, LF, A-weighted SPL, etc.
- Point response calculations including the stage parameters like C_{80}, D_{50}, ST_{early}, ST_{late}, ST_{total}, etc.

Auralisation

- Integrated Desktop Auralisation allowing audible evaluation and presentation using ordinary PC equipment with a sound card.
- OpenGL display showing rendered 3D images of the geometry, useful for verification of geometries material, receiver positioning etc.

3D Graphical Displays and Geometry Modeling

- Built in parametric modeling language (ODEON.PAR format) for fast modeling and remodeling of geometries.
- Full backwards compatibility with Odeon surface format (*.sur).
- Supports imports of DXF files, e.g. CAD and drawings exported from CAD.
- Tools for verifying geometries allowing the detection of wrapped surfaces, overlapping or duplication of surfaces, missing surfaces etc.

- 3D display visualizing ray tracing providing an efficient tool for evaluation of the room model investigation, revealing errors like misplaced or missing surfaces, etc.

2.7 Recent Studies

In recent years, the issue of poor classroom acoustics has been stated as one of the main reasons affecting better learning and understanding in education. A forgotten variable for many years, classroom acoustical properties are now being studied extensively and better design alternatives to enhance the acoustical conditions of educational facilities are being implemented. Educational institutions, audiologists and acoustical establishments all agree about the critical role of classroom acoustics in the modern learning process. Various acoustical organizations have already described guidelines for a better hearing environment for students while some are still preparing a universal standard for the acoustical characteristics of spaces for learning.

2.7.1 Classroom Acoustics and Learning

Most of the existing classrooms do not facilitate good acoustical conditions for learning [42]. Poor classroom acoustics interfere with listening, learning and ultimately academic achievements. Improving classroom acoustics also significantly reduces the negative educational impact of auditory disorders and also eliminate the so-called "acoustical barriers to learning". Specifications and standards for the regulation of airflow requirements for ventilation in classrooms are followed but the noise level created by heating and air conditioning units are often not appropriate for classroom learning. These ventilation systems need to be specifically designed to meet quieter standards. Financial decisions commonly favor the betterment of subsidiary items over ventilation systems with adequate noise control. Due to all these facts, students are made to learn in acoustical environments that cause fatigue and unsatisfactory listening conditions.

With the change in education methodology, learning these days occur during co-operative activities, classroom discussions or experimental learning. Even technology specifically designed to make speech signals stand out in a background of noise, such as FM technology and other equipment that enhance SNR can be seriously compromising when excessive background noise levels or reverberation exist in classroom. Communication in classroom often occurs in less than ideal acoustical conditions and is complicated by multiple talkers, noisy rooms, reverberant walls and sound obtrusive furniture. Recent findings by the American Speech-Learning-Hearing Association (ASHA) on the noise conditions of unoccupied and occupied classrooms also suggest that most classrooms in the United States of America (USA) are below the requirements for good understanding [43]. The noisiest classrooms were those with noisy heating, ventilating and air conditioning units (HVAC) running. Most of the classrooms exceeded ASHA recommendations even when the HVAC systems were turned off. Noise from other internal equipment and outdoors added to the total noise inside the classrooms. Classroom noise from HVAC system and other noise sources cause significant multiple teaching problems including teacher vocal fatigue and student off task behavior. These consequences lead to the learning deficits experienced by students in noisy rooms [44]. Although classroom sound amplification systems are partial solutions, adding amplified sound through loudspeakers into an already noisy and reverberant enclosure causes additional problems without providing significant improvements in the classroom acoustics.

When a high noise level is already present in classrooms, amplification sound levels may need to exceed 85 dB in order to achieve +15 dB throughout the room [44]. High levels such as this can be annoying and cause spill over into adjacent rooms where walls and doors provide inadequate sound barriers. Exposure to such noise levels can result in an unexpected increase in sound level due to reflective walls, floor and ceiling. The classrooms become significantly louder than before causing inconvenience to student's speech and hearing. It is essential for educational establishments to address classroom noise and reverberation or classroom acoustics through quieter HVAC systems and room architectural features.

In November 1999, the Access Board U.S.A. announced its plan to collaborate with private industries on the development of standards for classroom acoustics. As announced by the Federal Register (US Govt.), the board is working with a group headed by the Acoustical Society of America (ASA) and the American National Standards Institute (ANSI) to develop these standards through ANSI consensus process [45]. The other organizations in the team are the American Speech-Language-Hearing Association (ASHA), the American Federation of Teachers (AFT), the American Institute of Architects (AIA), the Council of Educational Facilities Planners (CEFPI) and the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE). The finalized report by the Access Board will be able to reference this standard as a notice in its Americans with Disability Act (ADA) accessibility guidelines. The standard also could be referred as U.S. Department of Education regulations covering proposed federal assistance for classroom construction.

In preparation for rule making, the Access Board published the classroom acoustic notice. For the first time an authoritative federal source stated specific criteria for acoustics in classrooms. The position statement recommended the following:

- Unoccupied Classroom noise levels should not exceed 30 dB
- S/N at the student's ears should exceed a minimum of 15 dB
- RT should not exceed 0.4 seconds

Considering the negative effects of noise in classrooms due to HVAC systems, ASHRAE organized a seminar to address the same issue in Chicago on January 1999 [46] on the theme "HVAC noise in classrooms: overcoming barriers to learning". The seminar was in conjunction with the Access Board initiative with classroom HVAC system selection and design as the main concerns. The problems of higher background noise due to HVAC systems, recommended Noise Criteria (NC) and Room Criteria (RC) ratings of these systems. The effect of air supply and diffuser selection/location and the cost tradeoffs for classroom acoustical criteria were the issues discussed in the seminar. A review of acoustical design criteria for HVAC systems was described and it was concluded that a C-Weighted scale which is more responsive to low frequencies generated by HVAC systems be preferred over an A-Weighted scale. Also the application of Balanced Noise Criteria (BNC) over the conventional NC & RC was recommended as it was noted that BNC is a good indicator for background noise if speech is the primary concern. Guidelines for the selection and design of HVAC system components for classrooms and educational establishments were also discussed in the form of an ASHRAE publication [47], which highlights the usage of conventional HVAC system components for classrooms. Brief lists of their recommendations are as follows:

1. HVAC systems that should be avoided in classroom applications are:
    - Self-contained AC units located in classroom

- Roof top AC units located in classroom
- Water source heat pump above classroom ceiling
- Any unit mounted in window or wall

2. Air distribution system should be low velocity system to minimize flow-generated noise and to minimize static pressure requirements on supply fan.
3. System fans which generate minimum noise should be selected for maximum efficiency.
4. Selection of diffusers in classrooms should be at least 3 NC point less than nominal design NC criteria. Addition of diffuser should have doubled NC point less than conventional specification.
5. Angles and location of bends in ductwork should be checked before construction for noise control.
6. Supply ducts should be above corridors and branch ducts should be low-pressure drop conical tee fitting.
7. Fan powered variable air volume (VAV) boxed should be located above corridors and not over classrooms.
8. VAV boxes located above classroom ceiling should be selected properly with recommended NC ratings with inlet duct as round spiral pipes, not flex duct.
9. Air handling units (AHU) should be located away from classrooms and other noise sensitive spaces.

10. Supply fan in central AHU should be selected for maximum efficiency and minimum noise generation with usage of vibration isolators essential.

2.7.2 Acoustical Investigation in Classrooms

A series of investigations have been performed to assess the characteristics of classroom acoustics. The initial studies concentrated on identifying the predictors that gave accurate prediction of SI in classrooms. A study by *Bradley (1985)* [14], included SI tests and acoustical measurement in ten occupied classrooms with the basic aim to identify the predictors that precisely evaluated the SI characteristics of a classroom. Octave band measurements of background noise levels, EDT and RT as well as early/late sound ratio, center time, U along with STI were obtained. To evaluate the appropriate predictors of SI in classrooms, the interrelationship of these measurements were verified. The conclusion was that STI and U_{35}, U_{50} values were the most accurate predictors of SI for classrooms. The optimum RT for classrooms was estimated to be in the range of 0.4 to 0.5 seconds, which is shorter than many standard references suggested earlier on. To accommodate all age groups, a background level should be limited to 30 dB.

University classrooms studied by *Hodgson, Rempel and Susan Kennedy (1998)* [48], at the University of British Columbia were evaluated along with a method for determining the typical long-term speech background noise levels during lectures. A model was developed that gave the combined effect of speech, HVAC system noise, student activity noise and outdoors generated noise. Lectures were recorded, digitalized and processed to obtain sound pressure level (SPL) frequency distribution to which three normal distribution curves were fitted. Long term SPL associated with the speech sound attained the maximum value curve while the other low value curves represented the ventilation noise and student activity noise. An empirical model was developed to predict the room average A-Weighted results using multiple variable regression analysis. Further analysis in the 63 to 8 kHz octave band confirmed the spectrum of ventilation and speech noise along with the spectrum of student activity noise and the S/N ratio. The model efficiently highlights the components of background noise and speech problems faced in classrooms for learning.

The effect of room acoustical characteristics as well as speech to noise ratio on SI in classrooms was studied by *Rebecca Reich and J. Bradley (1998)* [26]. Investigations for optimum acoustical conditions for classrooms were carried out using ODEON room acoustics computer model. Acoustical characteristics were accessed in terms of C_{50} and U_{50}. Optimum RT along with the optimum placement of absorption material was achieved for maximum SI. The results showed that a range of RT from 0.3 to 0.6 led to almost the same SI. The ambient noise level has a direct bearing on SI and the optimum RT also depends on the ambient noise levels. However, optimum conditions can be achieved by adding sound absorbing material, which affects the clarity and speech sound levels. Maximum speech clarity was achieved with insulation placed on the upper portion of the side and rear walls of the classrooms. This configuration would be appropriate in noisier conditions but its influence again depends on the ambient noise. Thus, depending upon the expected ambient noise, each classroom would require a different configuration of absorption materials with placement of the same on the upper portions of the walls considered as a general recommendation.

A brief prepared by *John Erdreich (1999)* [49] for the Council of Educational Facility Planners highlighted the issues of poor classroom acoustics by comparing them to "dark classrooms". The brief underlined the concerns of predicting classroom adequacy for communication with a comparison between the effects of varying AI, RT and S/N on SI. The influence of various geometrical shapes and finishing aspects of classrooms influence the acoustical properties of classrooms was also discussed. The effect of background noise due to the HVAC system and other sources has been studied in various combinations of classroom physical characteristics. In the form of guidelines, recommendations for new design or retrofits were described for general application.

Research on acoustical features of university classrooms by *Murray Hodgson (1999)* [11] examined 30 university classrooms in the University of British Columbia (UBC) with respect to their main physical and acoustical characteristics. The main aim was to elucidate the acoustical criteria of university classrooms in terms of their design and to determine the acoustical qualities of the classrooms at UBC. Randomly selected classrooms were tested for both occupied and unoccupied conditions. SI predictors like sound level, EDT, STI and RT were measured and compared along with the combined effect of S/N and RT in both occupied & unoccupied classrooms. The optimum design for classrooms was found to be dependent on the background noise levels, room geometry and acoustical treatment. The results proved that unoccupied classrooms in the UBC lacked acoustical quality. However, the scenario improved when the class was completely occupied, thus pointing out that a compromise between the parameters in question should be considered while designing classrooms.

Another study by *Bradley and Bistafe (2000)* [8], studied the effect of varying the sound-absorbing material treatment in a simulated classroom, comparing it with analytical and computer predictions of reverberation time. Seven contemporary analytical expressions and two room acoustics computer programs, RAYNOISE 3.0 and ODEON 2.6 were compared in a simulated classroom with varied absorption treatments. The research concluded that the average relative errors of most of the analytical formulae and computer programs for calculating RT ranged from 17% to 25%, which is quite high. The inaccuracy in the RT is found to be due to the sound field being less than ideally diffused. The amount and distribution of sound-absorbing material also appear to play a major role in the degree of diffusion of the sound field.

As an extension of the above research, *Bradley and Bistafa (2001)* [25] explored the speech matrix predictions in a simulated classroom again varying the absorption characteristics. Prediction of speech levels, C_{50} and STI were compared using analytical and two hybrid ray tracing based computer programs used earlier (i.e., RAYNOISE and ODEON). RAYNOISE computation with both the purely specular reflection model and the calibrated diffused reflection model were achieved while ODEON's Transition Order (TO) which changes the reflection procedure specular to diffused state was obtained. Comparing the results of these two software models, it was found that the ODEON model was more accurate than that of the RAYNOISE as also concluded in their earlier study [8]. Due to the accuracy and contemporary usage of ODEON software by acoustic consultants, researchers and universities, the same program will be used to model classrooms in this study.

With the growing perception that poor acoustics is a serious obstacle to learning and the initiative of the Access Board to introduce a standard regulation for classroom acoustical features, *David Lubman and Louis*

Sutherland (2000) [50,53] as active members in the research team investigated the various aspects of better classroom acoustics and design guidelines. In addition to this they addressed the most important issue which acts as an obstacle to the adoption of classroom acoustical optimization, that is the cost factor. Earlier on, acoustics was perceived as a cost with no apparent benefits but now with more awareness, the importance is being realized with the cost as a controlled and less expensive affair.

Lubman and Sutherland have worked out a cost analysis with examples showing the estimated figures for acoustical treatment, which were contributed by various organizations involved in the standard formulation. Table 1 shows the cost breakup of improving the Noise Reduction Criteria (NRC) of typical small classrooms. Cost analysis of acoustical improvisation of a gymnasium from RT_{60} of 6 seconds (unoccupied) to RT_{60} of 0.6 seconds resulted in a cost of $625 per year at $2 per square foot for new construction while it cost $1.25K per year at $4 per square foot in the case of a retrofit construction scheme, which showed the low cost involvement compared to the outcome of acoustical improvisation. Table 2 highlights the cost factor involved in the selection of a quieter HVAC system, with Table 3 combining the cost increments of both these elements. Another analysis on Table 4 shows the advantages in terms of reducing teacher absenteeism due to fatigue caused by poor classroom acoustics and also the impact of better classroom acoustics on the students. The validation of the data for teacher absenteeism is highly ambiguous in terms of its process & authenticity. However the author mentions its source as Educational Research Service (USA). Their research clearly proves the beneficial effects of good acoustics and the enhanced financial gains involved with investing in improving acoustics of classrooms.

Table 2.1. Estimated cost for suspended acoustical ceilings in typical classrooms [50].

Ceiling Absorption	NRC 0.55	NRC 0.75	Cost Difference
Total One time cost per room	$1054.50 to $1221	$1443 to $1610	$384
Cost per year (20 years lifetime)	$52.73 to $61.05	$72.15 to $80.48	$19.20
Cost per year per student	$2.64 to $3.05	$3.60 to $4.03	$0.97

Table 2.2 Estimated cost of quieter HVAC system [50].

HVAC Noise Design Goal	45 dB(A)	35 dB(A)
HVAC cost as percentage of total building cost	10%	14.5%
Cost per 1000 ft2 classroom	$10 K	$ 14.5 K
Total cost per 1000 ft2 for quieter HVAC to 35 dB(A)		$4.5 K
Cost per year (20 year service life)		$225
Cost per student per year (Average 20 students per room		$11.25

Table 2.3. Incremental cost for improved classroom acoustics [50].

Cost Element	Cost per ft^2.
Quieter HVAC: 35 dB(A) down from 45 dB(A)	$ 4.50
Higher ceiling absorption: NRC 0.75 up from NRC 0.55	$ 0.38
Total	$ 4.88

Table 2.4. Cost effect due to teacher absenteeism because of vocal fatigue [50].

Number of days a teacher loses per year due to vocal fatigue	2 days/ yr
Annual cost of substitute teacher	$ 210
Number of teachers in various educational facilities	2.7 million
National cost	$ 567 million annually

A recent study by Hodgson [50] discusses the contradictory results achieved through experiments and theoretical models for achieving the optimum RT. Experiments under various speech-signal to background noise level difference and RT result in an optimum RT of zero while theoretical predictions of an appropriate speech matrix based on diffused theory found a non zero optimal RT. The author explains that the cause of these contradictions is the unrealistic manner in which both methods account for the background noise.

To obtain accurate predictions, the noise source needs to be accounted in the diffused sound field theory and by considering the effect of RT for both speech and noise. The results show the RT to be zero when the speech source is closer to the receiver while it is non-zero when the noise source is closer to the listener. The developed model calculates the values of U50 as a function of RT, speech to listener distance, speech source output level, noise-source to listener distance and noise source output level, and noise source directivity indices. The research reiterates the optimization methodology of RT in occupied classrooms by optimizing un-occupied classrooms utilizing the diffused field theory.

CHAPTER 3

3.0 ACOUSTICAL EVALUATION OF EXISTING CLASSROOMS

3.1 Introduction

Behavior of sound in a classroom like any other enclosure depends upon the physical characteristics of the room. Various acoustical indicators can be used to assess the effect of the room enclosure on SI as described in Chapter 2. In order to be familiar with the behavior of sound in a smart classroom and its SI qualities, it is necessary to study sound behavior in existing classrooms particularly those with a potential to convert to smart classrooms. This will permit the following:

1. Enhancement of the understanding of the influencing acoustical parameters on SI in a smart classroom.
2. Study of the impact of new features and instructional equipment, which are integral part of the smart classroom.
3. Provision and assessment reasonable assumptions related to inputs required for the modeling and simulation of a smart classroom.

To fulfill the above-mentioned necessities, a survey of classrooms within the KFUPM campus was conducted to identify classrooms that could possibly house a smart classroom. The acoustical characteristics of the selected classrooms were measured with respect to the room size and surface finishes, and the bearing of the same on the acoustics of these spaces. The measured data was analyzed to verify the SI aspects in selected classrooms. The analysis highlighted the SI issues of the existing classrooms and the effect of room physical and spatial conditions as well as the background noise within these spaces on the overall acoustical performance. The evaluation gave a better idea of the SI parameters within existing classrooms and a practical understanding of the room acoustics in enclosures meant for learning. This information will later be utilized in the modeling of a typical smart classroom.

3.2 Classroom Selection Criteria and Characteristics

A survey was conducted on the KFUPM campus to shortlist classrooms depending upon their possibility to be used as a smart classroom with respect to their size, geometry and the representation of these classrooms as a major portion of KFUPM learning spaces. The short list was further narrowed on the basis of similar geometrical and physical configuration of some classrooms. One classroom was selected out of these identical rooms to represent all of them. The final selection of the variant classrooms was guided by the following basic criteria.

a. Size of the classroom, its geometry and capability to accommodate at least 20 computer workstations.
b. The uniqueness of the classroom or its physical representation of most or few of the university classrooms.
c. Existing surface finishing of the classroom that affects the acoustical ambience within the space.
d. The reverberance characteristics of the classroom.
e. Background noise levels in the unoccupied classroom and the cause of this noise.

The classrooms selected using the above-mentioned criteria also represent an average classroom configuration with surface finishing commonly used in most of the university classrooms with noise sources usually present in university classrooms all around the world. The survey of classrooms all around the KFUPM campus thus yielded the selection of six classrooms for acoustical measurements, four of which are regular classrooms and two are computer laboratories with display and data projection facilities. Table 3.1 shows the list of selected classrooms along with their physical characteristics and capacity. Each sample classroom was physically measured and documented graphically as shown in Figure 3.1(a). Based on existing classroom documentation, the acoustical measurement methodology and details were worked out.

Four of the selected university classrooms have lightweight carpeted flooring and the remaining two classrooms are finished with terrazzo hard flooring. The walls are hard plaster finished or are made up of aluminum-framed partition paneled with aluminum or glass panels. The false ceiling is paneled with porous metallic panels or acoustical gypsum panels. The front wall houses the blackboard along with a rolled plastic projection screen. In addition, small panels of cork or rubber are installed on certain walls, the proportion of which is too small to be considered as acoustically influencing wall mounting. The furniture is made up of plastic or polished wood rendering it highly reflective surfaces. Figure 3.1(b) and (c) shows the interior views of one of the selected university classroom (19-336). All the selected classrooms are lit by fluorescent lamps, which at times are also a source of noise in addition to the HVAC system noise. To provide natural light, at least one wall of these classrooms has a large or small percentage of glazing allowing a certain degree of external noise to intrude into the learning spaces. The documentation of the sample classrooms provided a better understanding of the typical physical characteristics of university classrooms. The difference and variation in the physical aspects of these enclosures can thus be compared once the SI indicators are measured and analyzed.

Table 3.1. Geometrical characteristics of the selected classrooms.

Ref. No. Bldg. #-Room#	Use	Dimensions, m			Aspect Ratio	Area	Capacity (P)	Volume (V)	V/P
		L	W	H	L/W	m^2	Person	m^3	m^3/P
7-121	CR	8.8	6.8	2.8	1.3	60	35	165	4.7
14-105*	Lab	12	5.8	2.5	2.0	70	30	184	6.1
19-336	CR	9.8	5.8	3.6	1.7	70	30	184	6.1
24-115	PR	10	8.5	3.5	1.2	85	35	300	8.5
25-236	CR	8.5	5.8	3.5	1.5	50	30	175	5.8
25-236**	Lab	12	7.2	3.5	1.7	70	26	300	11.5

Legend:

* Room also measured for instructional equipment noise.

** Room measured for instructional equipment noise only.

CR Classroom

Lab Laboratory

PR Presentation Room

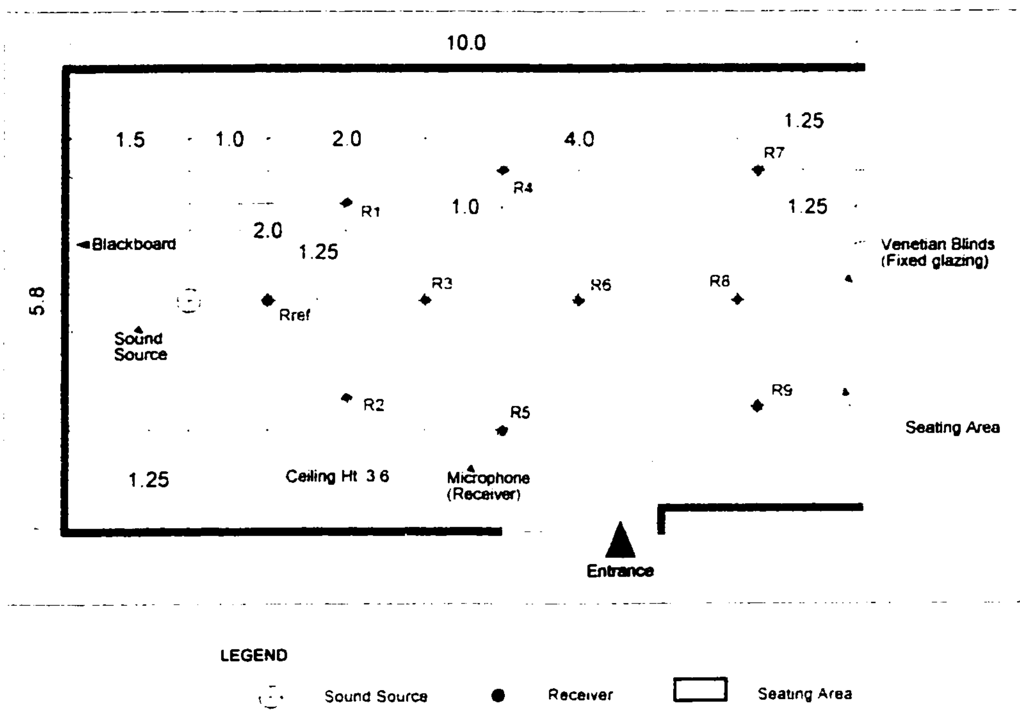
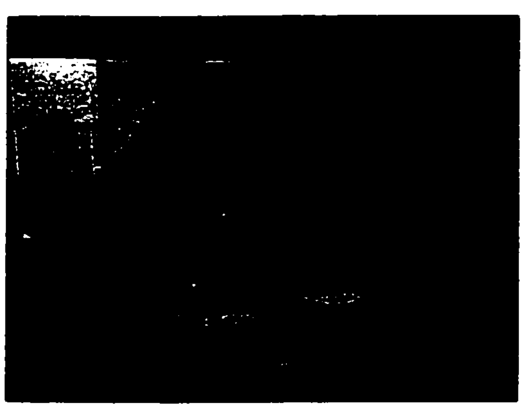


Figure 3.1(a). A typical documentation of a sample classroom. Test sound source and measurement locations are also shown.

General Information:-

Classroom reference number:	19-336
Dimensions (L x W x H):	9.85 x 5.8 x 3.6 (m)
Room aspect ratio:	1.7
Volume (m^3):	205
Capacity (persons):	55

Usage: Regular classroom



(b)

(c)

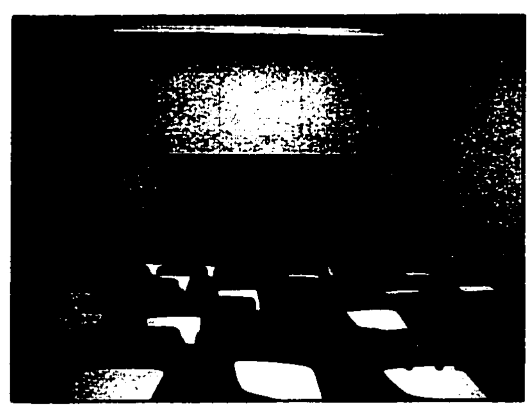


Figure 3.1 (b) and (c). Interior views of classroom 19-336

3.3 Measurement Setup and Procedure

Three measurement setups were used to investigate the acoustical characteristics of the sample classrooms (see Table 3.1 for selected sample classroom details). The devised setups allow systematic measurement and analysis of the SI indicators to achieve the objectives of this study. Each setup measures particular acoustical parameter for objective sound quality evaluation.

3.3.1 Measurement System Procedure

To characterize and evaluate the acoustical performance of the selected learning spaces, the Maximum Length Sequence System Analyzer (MLSSA) is used. A PC based powerful audio and acoustical measurement system, the MLSSA is a single channel analyzer that can work as a conventional dual channel analyzer utilizing a signal referred to as a Maximum Length Sequence (MLS) to obtain the room Impulse Response. Contrary to the conventional white noise, an MLS signal is deterministic and periodic yet still retains many desirable characteristics of white noise. The MLSSA signal channel analyzer results in an effective doubling of useful bandwidth and a significant reduction in cost. The Fast Fourier Transformation (FFT) analyzer requires two channels to measure the system transfer function using white noise as a stimulus [55]. One channel samples the input noise while the other samples the resulting system output. The transfer function is then estimated using the cross-spectra or similar method. The MLS technique measures the Impulse Response (IR), the most fundamental descriptor of any linear system from which a wide range of important functions are derived through computer aided post processing [55]. MLSSA computes and analyzes important acoustical parameters necessary for room-acoustical evaluation and diagnostics.

MLSSA directly recovers the IR's in the time domain without using Fast Fourier Transfer (FFT) or inverse FFT. An important advantage of using the MLS signal is the ability to obtain wideband long duration IR measurements containing up to 65535 points. In addition the MLSSA system includes all the post-processing algorithms needed to extract all the results obtainable by FFT measurements from the measured IR's. A typical MLSSA impulse response measured in a sample classroom is shown in Figure 3.2.

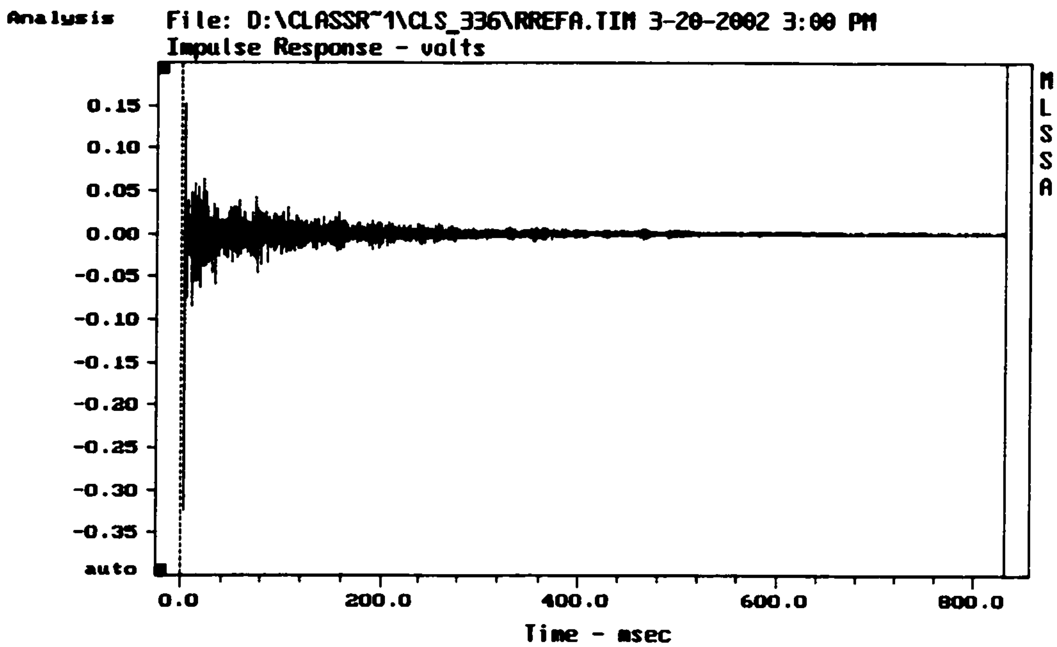


Figure 3.2. A typical impulse response measured by MLSSA.

3.3.2 Measurement Setup I: Room Acoustical Indicators

The measurement setup I was used to measure room acoustical indicators that are suggestive of SI characteristics of a space such as RT_{30}, C_{50} and D_{50}. MLSSA was used for the measurement along with an omni directional sound source (loudspeaker). Figure 3.3 shows a conceptual sketch of the measurement layout and the components of the setup I with Figure 3.4 displaying the measurement equipment. The omni directional sound source excites the room uniformly in all directions. The loudspeaker was located 1.5 m from the front wall of the classroom along the centerline of the room as denoted by S_1 in Figure 3.1. This location represents the typical location of the instructor with the loudspeaker placed at a height of 1.6 m to mimic the instructor in a standing position. Measurement was then conducted at the farthest receiver location from the sound source with a constant MLS signal providing a sufficient dynamic range for accurate processing of data on all receiver locations.

Figure 3.5 (a) and (b) depicts the MLSSA impulse response acquired at receiver locations R1 & R6 respectively in classroom 19-336. Figure 3.6 displays the SPL value range measured at nine locations in the same classroom at octave-band frequencies showing the level and frequency content of excitation signal received at the nine receiver locations. Depending upon the size and configuration of the classroom, 8 to 12 listener positions were selected to achieve a uniform coverage of the classroom floor area in accordance with ISO 3382 [56]. The distance between any two-listener positions always exceeded 2 m while the distance from any reflecting surface was kept at 1.25 m, which is almost equal to half the wavelength of the lowest-band frequency of interest, that is 125 Hz. The selection of the listener location was also in conjunction with noise sources within and around the classroom.

Measurements were acquired using an ACO Pacific model 7012, ½" condenser microphone mounted on an adjustable holder fixed to a tripod and the microphone was maintained at a height of 1.2 m from the floor representing the position of the listener's ear. The microphone was calibrated using a precision microphone calibrator Cirrus Model 511E before carrying on the measurements. The measurements were processed using one octave-band frequency ranging from 125 Hz to 8 KHz. The analysis of the measured IR's was confined to a frequency range of 125 Hz to 4 kHz as per ISO 3382 [56].

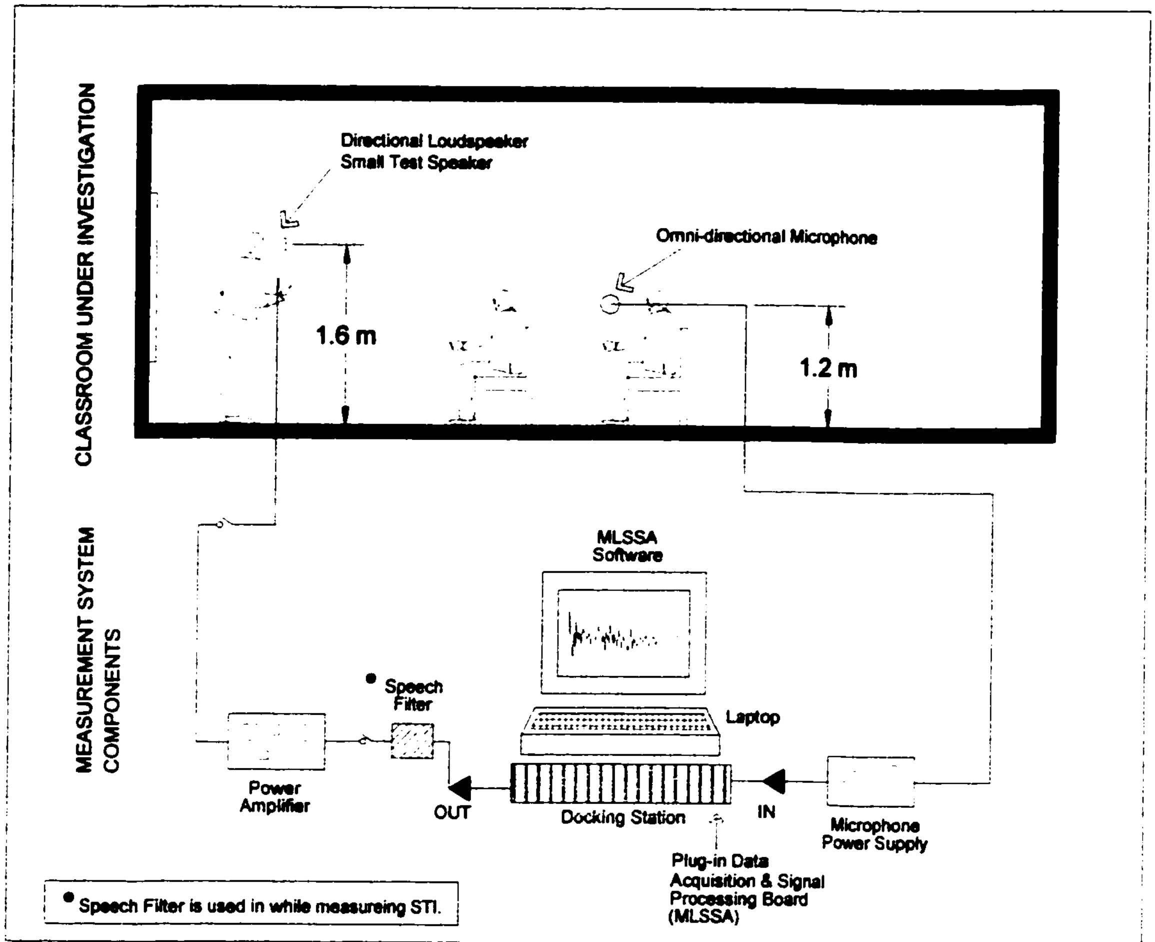


Figure 3.3. Conceptual measurement layout and setup components.

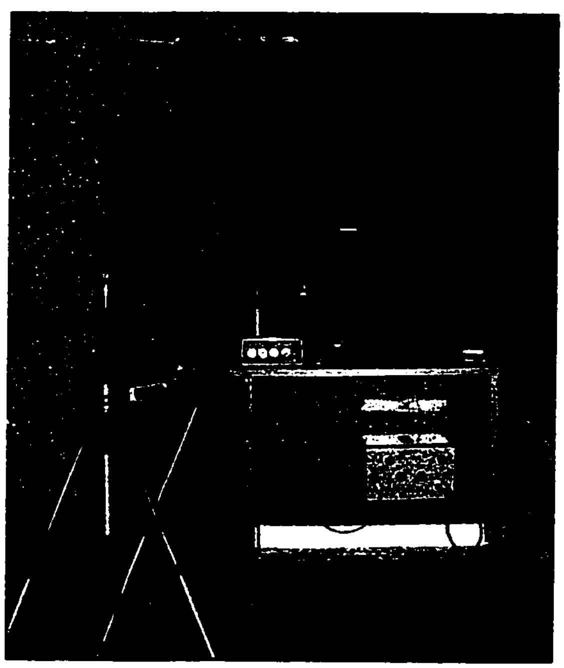


Figure 3.4. A picture of the equipment used for measurements.

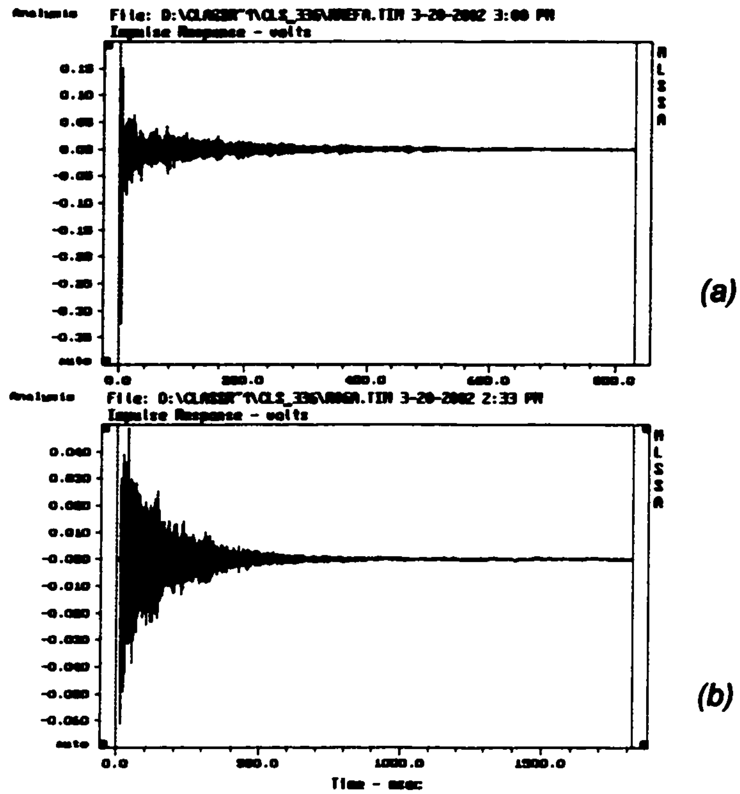


Figure 3.5. *Impulse response as measured by MLSSA using setup I. Part (a) The IR at reference point while part (b) the IR at location R6 in the same sample classroom (19-336).*

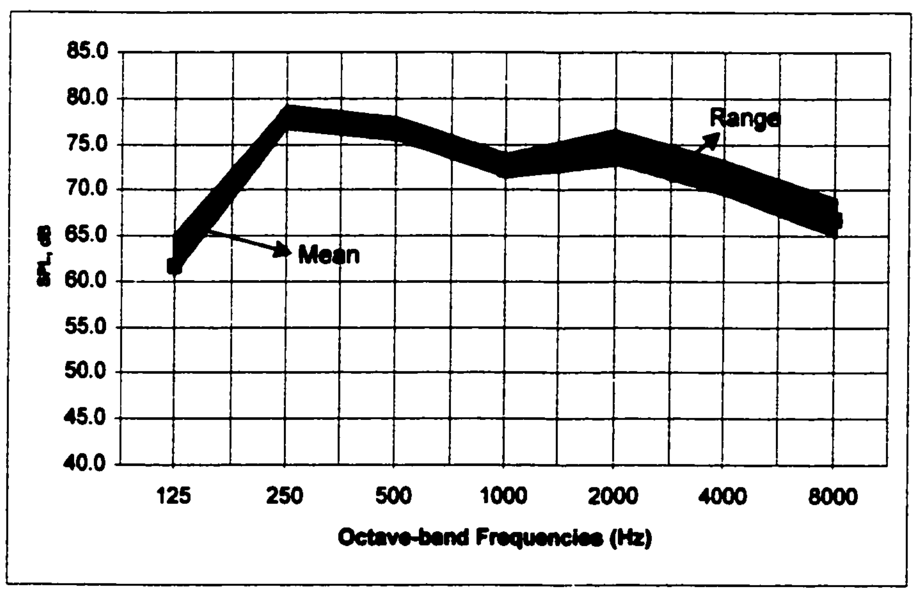


Figure 3.6. The SPL spectrum range of the sound signal in the frequency range of interest

3.3.3 Measurement Setup II – Background Noise (BN)

Another MLSSA measurement setup was used to measure the BN level in the selected classrooms. The MLSSA was configured to measure the SPL of ambient noise determined in the standard octave bands. In addition to this, MLSSA generates the overall A-weighted sound level and displays the Noise Criteria (NC) rating of the BN. The NC rating is defined as the lowest NC curve that is not exceeded by the actual octave-band noise spectrum. The ambient noise levels were measured in the selected locations along the selected classrooms utilizing the same calibrated ½" condenser microphone located at a height of 1.2 m to mimic the human ear. A sound signal of 65535 points with a length of 1081msec was acquired and spectrally averaged 32 times during the acquisition process. While acquiring the measurement, precautions were taken to ensure that no intruding or unrealistic noise hampered the acquisition of ambient noise resulting in exaggerated NC rating.

3.3.4 Measurement Setup III: Speech Intelligibility

With the acquisition of a long duration IR, the MLSSA calculates Speech Transmission Index (STI), one of the major objective indicators of Speech Intelligibility (SI) as described in Chapter 2, along with its simpler version Rapid STI (RASTI). STI and RASTI are derived calculations based on the Complex Modulation Transfer Function (CMTF). The MLSSA analyzes the impulse response in 7 octave bands and 14 modulation frequencies [55]. It also calculates $\%Al_{cons}$ from the over all STI value. STI and RASTI measurements carried out by MLSSA properly account for the background noise provided the MLS stimulus is first passed through a speech-weighing filter prior to applying it to the system to be measured. In this setup a speech-weighing filter was used. Speech intelligibility is also affected by the directivity factor of the un-amplified speaker in a classroom so a small test loudspeaker was used and located at 1.55 m height from the floor. The A-weighted SPL of the generated MLS signal at a location 1.0 m directly in front of the test loud speaker was adjusted to achieve an A-weighted SPL of 67 dB(A). Measurements were taken in all sample classrooms at selected locations at a height of 1.2 m, which represent the listener's ear. The overall STI values generated by MLSSA are in accordance with the weighting factor described in chapter 2 [23].

3.4 Measurements and Analysis

The three measurement setups described earlier were tested in the laboratory for their appropriateness and to detect possible deficiencies before proceeding with the measurements in the selected classrooms. Measurements were conducted with all three setups in the sample classrooms and on completion of each of the classroom measurements, the data was processed and analyzed. The analysis methodology, details and interpretation of results of one of the classroom referred to as 19-336 are described below to explain the systematic analysis followed in all the other sample classroom measurements.

The architectural documentation of classroom 19-336 illustrated in Figure 3.1, also describes the location of selected measurement points and the positioning of the sound source. In this case due to the configuration of the student seating area, nine listener locations denoted as R1 to R9 were examined that would be representative of the student seating area. The locations were also selected in conjunction with the HVAC noise outlets basically to provide the comparative effect of the HVAC noise at locations closer and farther away from it.

The IR's acquired using Setup I were processed and analyzed. Table 3.2 shows the measured values of RT_{30} in octave band frequencies from 125 Hz to 8 KHz for all the nine measurement points. Average values of middle frequencies 500 to 1000 Hz and 500 to 2000 Hz were calculated for each measurement point and are shown in the last three columns of Table 3.2. The lower three rows show the spatial minimum, average, maximum and standard deviation values of RT_{30}.

The average RT_{30} within mid frequencies of 500 to 1000 Hz was noted as 1.10 sec in un-occupied conditions with a maximum of 1.2 sec. The RT_{30} is much higher than the recommended RT_{30} range of 0.4 to 0.6 sec [1,51,54] for classrooms. With a sound absorption of 0.45 metric sabins per student seated on a table armchair [4] at mid frequency range of 500-1000 Hz, the RT_{30} in fully occupied classrooms would be around 0.62 sec, while for 2/3 and 1/3 occupancy state, the RT_{30} would be 0.71 and 0.85 sec respectively. In fully occupied conditions, the RT was thus found to be barely optimum while the same would be above the recommended RT_{30} value in the case of 2/3 and 1/3 occupancy. Figure 3.7 depicts the RT_{30} spectrum value range in this classroom (19-336). At low frequencies, the RT spectrum range was found to be higher and constant at high frequencies. A distinct variation was noticed at the mid frequency range of 500-1000 Hz.

For further evaluation of room acoustics the D_{50} values obtained from the measured IR's were analyzed. Table 3.3 depicts the D_{50} values at all the locations while Figure 3.8 shows the D_{50} spectrum value range. The mean value of D_{50} at mid frequency range of 500 to 1000 Hz was found to be around 52.6% with maximum of 64 % and a minimum of 42%. The mid frequency value was however within the optimum speech intelligibility range of 40% to 65% [13] while at certain locations have D_{50} values were noticed to be higher than the optimum value range.

Clarity (C_{50}) of speech, an important indicator of speech intelligibility, was calculated from the acquired impulse response. Table 3.4 describes the calculated C_{50} results at nine-selected location while Figure 3.9 illustrates the spectral range and the standard deviation of the same. The mean at the mid frequency was found to be approaching 0.0 dB varying from –1.4 to 2.5 dB with a standard deviation of 1.3 dB. The mid frequency value is within the optimum range required for satisfactory speech intelligibility.

Background noise of a classroom affects the speech intelligibility within the space. Using Setup II the background noise was measured at all nine selected locations in standard octave band frequency range from 63 to 8 KHz and the data was processed for analysis. Table 3.5 describes the background noise results with the mid frequency average between 500 to 1000 Hz, 500 to 2000 Hz, and 500 to 4000 Hz are shown in the right hand columns while the minimum, mean and maximum values are displayed in the lower rows. The overall A-weighted and linear SPL along with the Noise Criteria (NC) rating of the measured noise spectrums are shown in the last rows of the Table. Figure 3.10 depicts the background noise spectrum measured in the classroom (19-336). The results show the classroom noise rating as NC-40 with a noise level of 44.9 dB-A, which exceeds the recommended A-weighted steady BN level for a classroom that is 35 dB-A for a classroom volume less than 283 m^3 [54]. The NC rating was also found to be higher than the recommended range of NC 25 to NC 35. Thus the BN noticed in this classroom was much higher than the BN conditions for optimum SI. The RC Mark II [ASHRAE Applications 1999] evaluation of the mean BN spectrum highlights a rating of RC-40 'HF', the spectrum appears to be dominant in the high frequency range encountered with marginally problematic hiss. The RC rating was again higher than the recommended range of RC 25 to RC 35 for classrooms.

Using Setup III speech intelligibility indicators STI, RASTI and $\%AL_{cons}$ along with the overall SI rating was calculated for the selected receiver locations in classroom 19-336. Table 3.6 illustrates the values of these indicators along with their overall rating. The spatial minimum, mean, maximum and the standard deviation are derived in the lower rows of the Table. The results suggest a 'Fair' STI rating at all locations while RASTI values are 'Good' at locations closer to the sound source and the rating deteriorates as we move farther away from the sound source. The same results are evident from the STI and $\%AL_{cons}$ measurements. Figures 3.11(a) and (b) depict the STI, RASTI and $\%AL_{cons}$ spectrum comparing it with the distance from the sound source.

Table 3.2. The RT_{30} results measured at 9 listener locations.

Cls.19-336								Mean	Mean
R01	1.65	1.81	1.43	0.97	0.93	0.96	0.77	1.2	1.11
R02	1.66	1.71	1.36	0.89	0.94	0.94	0.76	1.1	1.07
R03	1.68	1.62	1.27	0.92	0.92	0.91	0.73	1.1	1.04
R04	1.83	1.69	1.27	0.91	0.93	0.92	0.74	1.1	1.04
R05	1.61	1.73	1.33	0.91	0.91	0.94	0.76	1.1	1.06
R06	1.83	1.56	1.27	0.93	0.91	0.94	0.757	1.1	1.04
R07	1.70	1.55	1.27	0.94	0.94	0.96	0.78	1.1	1.05
R08	1.71	1.61	1.31	0.97	0.95	0.99	0.81	1.1	1.08
R09	1.50	1.67	1.34	0.93	0.95	0.98	0.81	1.1	1.06
Minimum	1.51	1.55	1.27	0.89	0.91	0.91	0.74	1.1	1.04
Mean	1.69	1.66	1.32	0.93	0.94	0.95	0.77	1.1	1.06
Maximum	1.84	1.81	1.43	0.97	0.96	1.00	0.82	1.2	1.11
STD	0.10	0.08	0.05	0.02	0.01	0.02	0.03	0.0	0.02

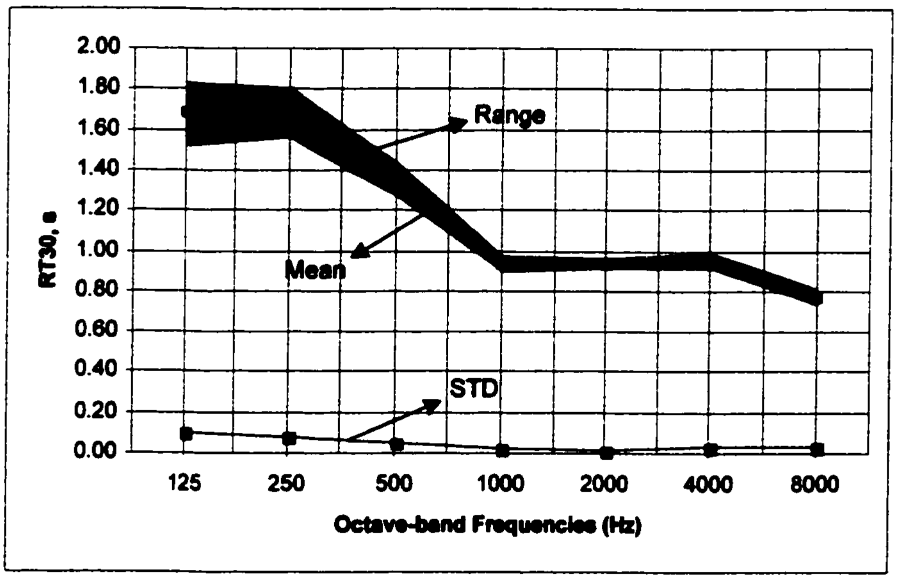


Figure 3.7. RT_{30} spectra range and the mean values at all 9 measurement points.

Table 3.3. The D_{50} results measured at 9 listener locations.

Cls.19-336								Mean	Mean
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
R01	42.3	47.2	51.6	64.7	72.9	70.5	73.8	[illegible]	[illegible]
R02	43.8	48.5	57	64.5	74.3	77.2	78	[illegible]	[illegible]
R03	42.1	33.3	63	65.4	69.6	76.2	81	64.2	[illegible]
R04	38.4	53.8	40.1	63.2	59.8	65	72.6	51.7	[illegible]
R05	39.4	31.7	48.1	64.1	63.8	66.8	71.1	[illegible]	[illegible]
R06	32.8	36.4	39.4	53.7	57.5	59.7	68.6	[illegible]	[illegible]
R07	58.9	24	33.7	57.2	59.5	58.3	66	[illegible]	[illegible]
R08	40.8	21.3	32.9	51.2	59.4	56.4	63.8	42.1	47.8
R09	26.1	26.8	40.6	56.6	60.9	55.5	71.2	46.6	62.7
Minimum	26.1	21.3	32.9	51.2	57.5	55.5	63.8	42.1	47.8
Mean	40.5	35.9	45.2	60.1	64.2	65.1	71.8	52.6	66.5
Maximum	58.9	53.8	63.0	65.4	74.3	77.2	81.0	64.2	[illegible]
STD	8.4	10.9	9.8	5.1	6.0	7.8	5.1	7.1	6.6

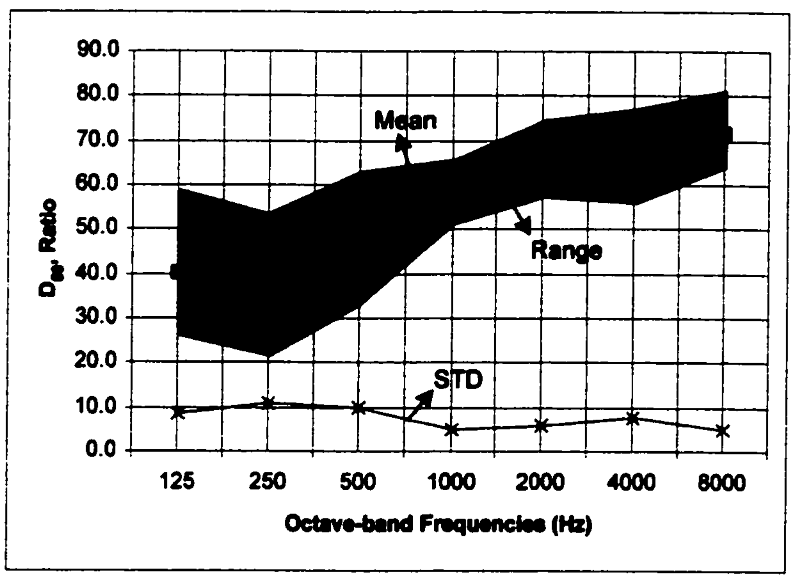


Figure 3.8. D_{50} values and its mean at all 9 selected measurement locations.

Table 3.4. C_{50} values at all the 9 measurement locations.

Cls.19-336								Mean	Mean
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
R01	-1.06	-0.48	0.28	2.62	4.29	3.79	4.51	1.9	2.4
R02	-1.08	-0.26	1.23	2.58	4.61	5.3	5.49	1.9	2.8
R03	-1.38	-3.02	2.32	2.76	3.6	5.06	6.3	2.5	2.9
R04	-2.06	0.66	-1.74	2.36	1.72	2.7	4.23	0.5	0.8
R05	-1.87	-3.33	-0.32	2.51	2.47	3.04	3.91	1.1	1.6
R06	-3.12	-2.43	-1.86	0.64	1.32	1.71	3.4	-0.5	0.6
R07	3.73	-5.01	-2.95	1.26	1.67	1.45	2.88	-0.8	0.0
R08	-1.62	-5.67	-3.09	0.2	1.65	1.11	2.46	-1.4	-0.4
R09	-4.53	-4.36	-1.64	1.15	1.92	0.96	3.93	-0.2	0.5
Minimum	-4.5	-5.7	-3.1	0.2	1.3	1.0	2.5	-1.4	-0.4
Mean	-1.4	-2.7	-0.9	1.8	2.6	2.8	4.1	0.5	1.2
Maximum	3.7	0.7	2.3	2.8	4.6	5.3	6.3	2.5	2.9
STD	2.1	2.1	1.8	0.9	1.2	1.6	1.1	1.3	1.2

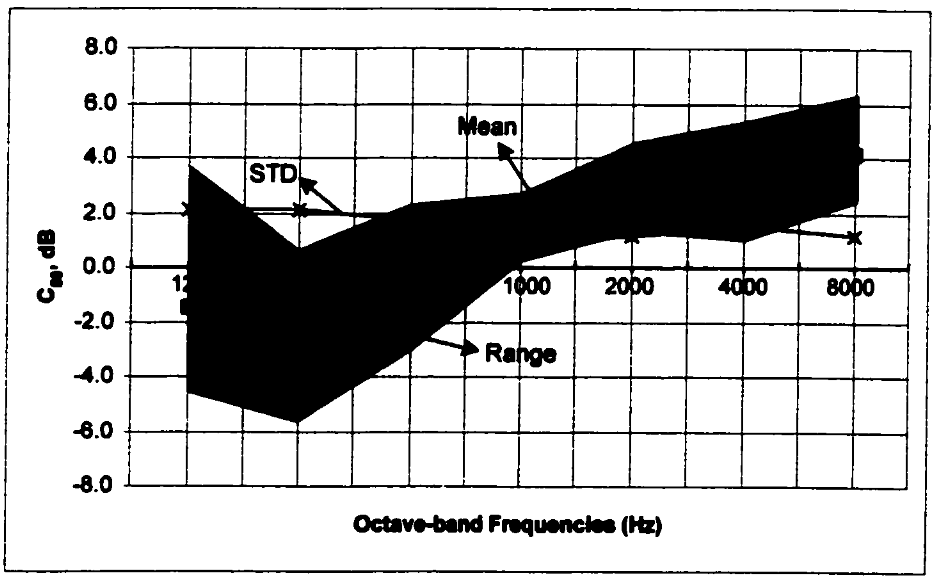


Figure 3.9. C_{50} value range and its standard deviation measured at all the 9-selected receiver locations in classroom 19-336.

Table 3.5. The background noise at the 9 measured locations with their mean and NC-ratings.

Cls: 19-336										Mean		Mean	Mean	
[illegible]	65.5	60.4	49.3	43.2	41.4	41.2	36.1	28.3	22.5	[illegible]	[illegible]	[illegible]		[illegible]
[illegible]	59.1	54.1	47.5	40.4	41.4	40.8	36.1	28.7	23.2	[illegible]	[illegible]	[illegible]		[illegible]
[illegible]	56.9	55.8	48.7	42.4	41.5	41.5	36.5	28.8	23.4	[illegible]	[illegible]	37.1		[illegible]
[illegible]	61	58	46.3	43.7	41.7	41.2	36	28	22.5	[illegible]	[illegible]	[illegible]		[illegible]
[illegible]	61.6	57.2	48.8	42	41.3	41.1	36.2	29.1	23.2	[illegible]	[illegible]	[illegible]		[illegible]
[illegible]	55.8	54.4	47.3	42.2	41.1	41.2	36	28.1	22.9	[illegible]	[illegible]	[illegible]		[illegible]
[illegible]	67.4	62.1	51.3	44.9	41.5	41.3	35.9	27.8	21.4	[illegible]	[illegible]	[illegible]		[illegible]
[illegible]	58.4	51.8	49.8	41.3	41.3	41.4	36	28.1	22.6	[illegible]	[illegible]	[illegible]		[illegible]
[illegible]	61.6	56.8	47.3	42.5	41.3	41.6	35.5	27.6	22	[illegible]	[illegible]	[illegible]		[illegible]
[illegible]	55.8	51.8	46.3	40.4	41.1	40.8	35.5	27.6	21.4	41.1	[illegible]	[illegible]		[illegible]
[illegible]	60.8	56.7	48.5	42.5	41.4	41.3	36.0	28.3	22.6	[illegible]	[illegible]	[illegible]		[illegible]
[illegible]	67.4	62.1	51.3	44.9	41.7	41.6	36.5	29.1	23.4	[illegible]	[illegible]	37.1		[illegible]
STD	3.6	3.0	1.5	1.2	0.2	0.2	0.2	0.5	0.6	0.1	0.1	0.2		[illegible]

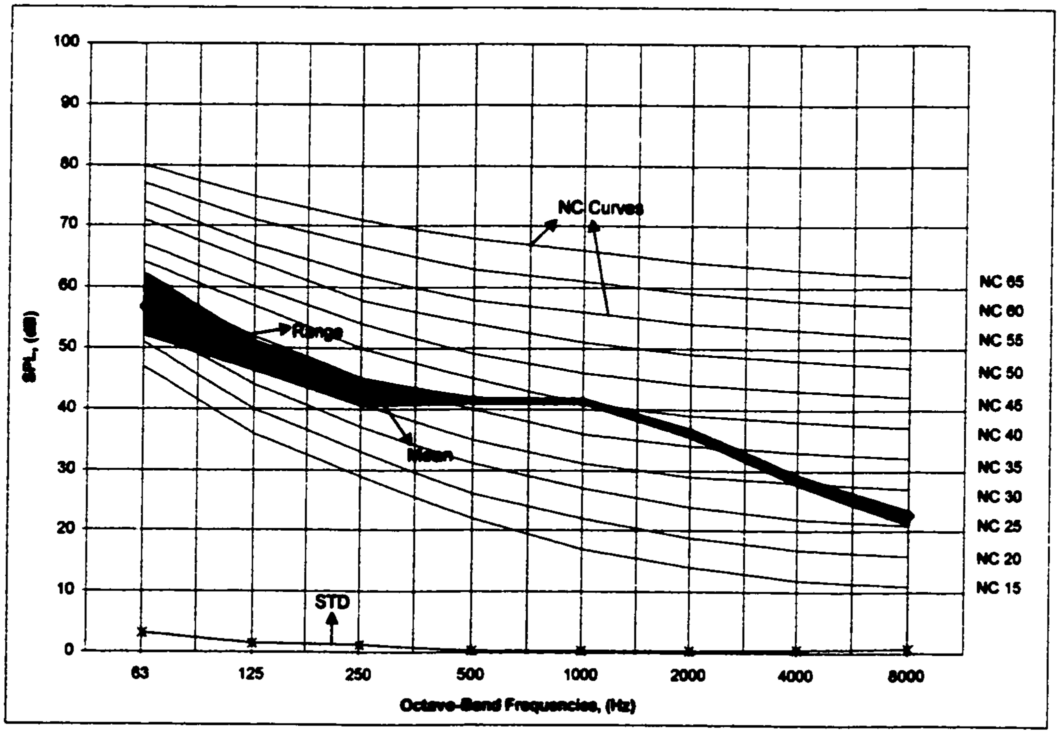


Figure 3.10. The background noise spectra range along with the NC ratings.

Table 3.6. STI, RASTI and $\%AL_{cons}$ measured at all 9 measurement locations.

Cls: 19-336			STI, Full			RASTI		
Point #	**Arrival Time, ms**	**Distance, m**	**STI**	**Alcons%**	**Rating**	**RASTI**	**Alcons%**	**Rating**
R01	6.49	2.23	0.54	9.2	FAIR	[illegible]	[illegible]	GOOD
R02	6.63	2.27	0.53	9.5	FAIR	[illegible]	[illegible]	GOOD
R03	5.62	1.93	0.56	8.1	FAIR	0.63	[illegible]	GOOD
R04	12.21	4.19	0.50	10.8	FAIR	0.54	[illegible]	FAIR
R05	12.63	4.33	0.52	10.2	FAIR	[illegible]	[illegible]	FAIR
R06	14.26	4.89	0.50	10.9	FAIR	0.57	[illegible]	FAIR
R07	20.45	7.01	0.48	12.5	FAIR	0.52	10.0	FAIR
R08	19.29	6.62	0.51	10.5	FAIR	0.56	[illegible]	FAIR
R09	20.48	7.02	0.50	11.2	FAIR	0.56	[illegible]	FAIR
	Minimum	1.93	0.48	8.10	FAIR	0.52	5.50	FAIR
	Mean	4.50	0.52	10.32	FAIR	0.57	7.64	FAIR
	Maximum	7.02	0.56	12.50	FAIR	0.63	10.00	GOOD
	STD	1.95	0.02	1.20		0.03	1.29	

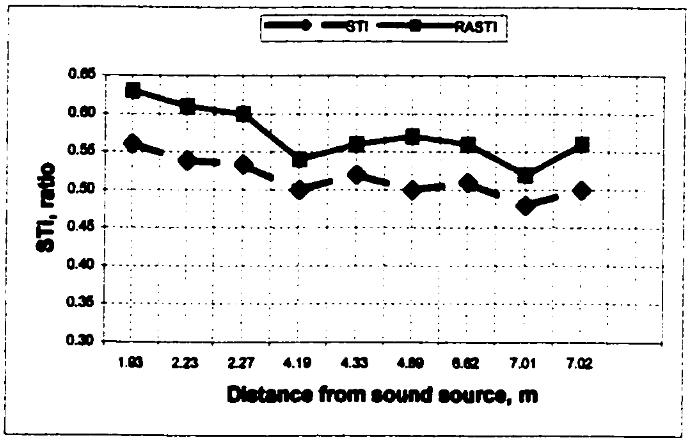


Figure 3.11(a). STI and RASTI values with respect to the distance from the sound source.

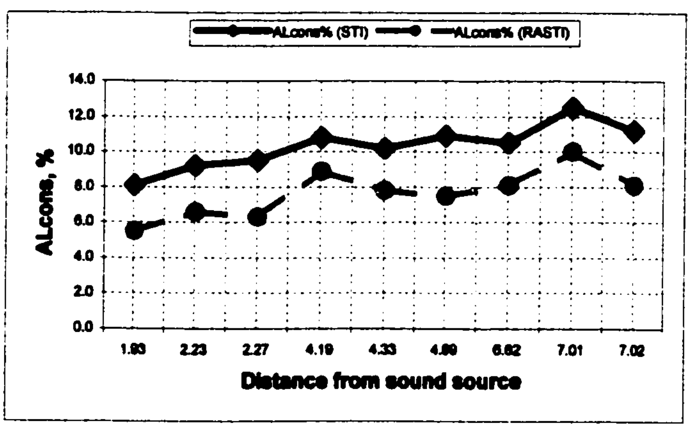


Figure 3.11(b). $\%AL_{cons}$ values for both STI and RASTI values versus the distance of the measurement location for the sound source.

3.5 Analysis of the Sample Classrooms Measurement Results

The measurement analysis described earlier for classroom referenced 19-336 was carried out for all the sample classrooms illustrated in Table 3.1. The evaluation of the acoustical performance of the sample classrooms is described in the following section.

3.5.1 Acoustical Indicators: RT_{30}, D_{50} and C_{50}

A comparative analysis of all the sample classrooms was carried out in terms of their measured acoustical indicators. Section A of Table 3.7 compares the mean values of all the five classrooms RT_{30} spectra in octave-band frequencies. Section B of the same Table describes the minimum, mean, maximum and standard deviation (STD) of all the measured classrooms, thus displaying the overall range of RT_{30} along with the overall average spectrum. In the right hand side columns of Table 11 the average values in mid frequency ranges of interest are presented. Average values in mid-frequency range of 500 to 1000 Hz are used to characterize the collective acoustical performance value of the particular indicator in question. The spectra range of RT_{30} measurements of all classrooms as well as the standard deviation are shown in Figure 3.12.

It can be observed from section B of Table 3.7 that the RT_{30} values in all the classrooms range from 0.55 to 1.1 sec with a mean RT of 0.75 sec and a STD of 0.2. The mean RT of one of the classrooms is found within the acceptable range of 0.4 to 0.6 [1] sec while the rest of the measured classrooms have a higher RT than the recommended RT range. Higher RT_{30} values are noted in the lower and mid frequency range in almost all the mean spectrums, which is detrimental for SI causing sound to blur as described in Chapter 2. The major area of the range of RT value spectra measured in the sample classrooms is found to be above the acceptable range as seen in Figure 3.12. In the mid frequency range, the minimum spectrum is within the recommended value of RT_{30} for core learning spaces which should however be much lower than observed. The average spectra of the studies university classrooms suggest the possibility of optimal RT in three classrooms when occupied which nevertheless will depend on the occupancy percentage. in general the RT values are greater than the optimum RT requirements for SI. However the reduction in average RT by 0.2 to 0.3 sec would bring the RT within the optimum range as recommended by the ANSI standard for classroom acoustics [54] in all possible occupancy conditions and hence results in improved SI.

The D_{50} value range along with the mean spectrum is illustrated in Table 3.8. The D_{50} value range at mid-frequency average of 500 to 1000 Hz varies from 53% to 77% with a mean of 69.7% and a STD of 8.8. The average D_{50} spectrum is found to be higher than the recommended value of 40 to 64% [13,57]. Figure 3.13 shows the spectral value range of D_{50} values along with the standard deviation.

Table 3.9 illustrates the C_{50} value range. It can be noticed that the mid-frequency (500- 1000 Hz) average ranges from 0.46 to 5.54 dB with a mean of 3.89 dB. Figure 3.14 shows the C_{50} spectra range and the standard deviation. Out of the five sample classrooms, four classrooms are found to have a mean C_{50} value of more than 4.0 dB in mid-frequency range while one of them with the highest mean RT of 1.13 has the highest mean C_{50} value approaching '0' value, that is 0.45 dB. However, most of the measured C_{50} spectral value range lies within the recommended clarity range of 0 dB to 5 dB for optimal SI [13,57].

Table 3.7. RT_{30} spectra range in octave-band frequencies along with the average values in various mid-frequency averages.

SECTION A									
	Octave-band Frequencies, Hz							Average	
Mean19-336	1.69	1.66	1.32	0.93	0.94	0.95	0.77	1.13	1.06
Mean 14-105	0.76	0.70	0.68	0.56	0.53	0.56	0.52	0.62	[illegible]
Mean 07-121	0.82	0.99	0.84	0.58	0.68	0.68	0.57	0.71	0.76
Mean 24-115	0.71	0.61	0.58	0.50	0.45	0.41	0.33	0.54	0.51
Mean 24-236	0.60	0.68	0.67	0.65	0.77	0.81	0.64	0.66	0.76

SECTION B									
Minimum	0.60	0.61	0.58	0.50	0.45	0.41	0.33	0.54	0.51
Mean	0.92	0.93	0.82	0.64	0.67	0.68	0.57	0.73	0.66
Maximum	1.69	1.66	1.32	0.93	0.94	0.95	0.77	1.13	[illegible]
STD	0.39	0.39	0.26	0.15	0.17	0.19	0.15	0.21	0.16

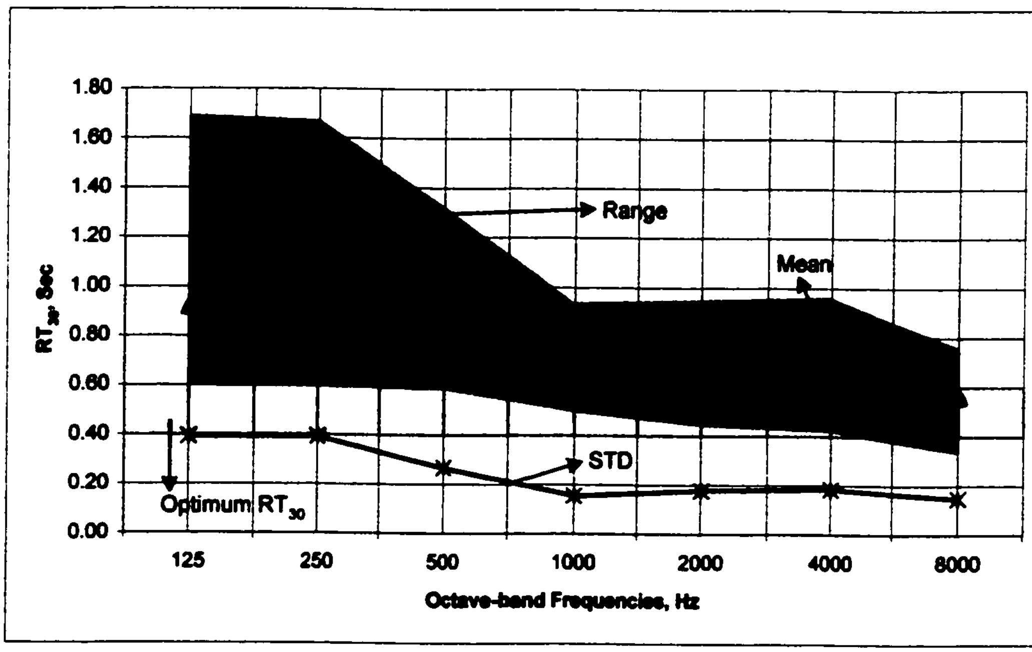


Figure 3.12. RT_{30} Spectra value range with the standard deviation.

Table 3.8. The mean D_{50} spectrum range in octave-band frequencies along with the mid-frequency averages.

SECTION A									
	Octave-band Frequencies, Hz							Average	
Mean19-336	40.5	35.9	45.2	60.1	64.2	65.1	71.8	[illegible]	[illegible]
Mean 14-105	57.71	70.61	69.7	74.6	78.7	80.8	85.3	72.1	74.3
Mean 07-121	66.44	64.8	67.9	77.1	77.5	78.9	83.9	72.6	74.2
Mean 24-116	67.15	75.02	73	82	85.3	87.7	91.8	77.5	80.1
Mean 24-236	73.5	69.88	70.3	77.6	79.8	80.6	86.4	73.9	75.9
SECTION B									
Minimum	40.5	35.9	45.2	60.1	64.2	65.1	71.8	[illegible]	[illegible]
Mean	61.1	63.2	65.2	74.3	77.1	78.6	83.9	68.7	72.2
Maximum	73.5	75.0	73.0	82.0	85.3	87.7	91.8	77.8	80.1
STD	11.4	14.1	10.1	7.5	7.0	7.4	6.6	8.8	8.1

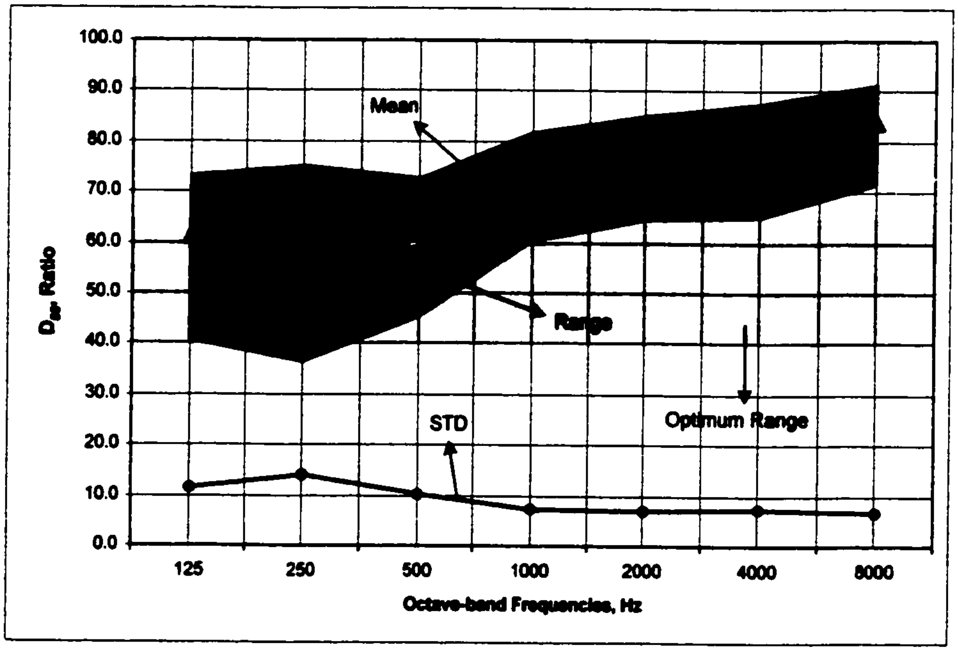


Figure 3.13. D_{50} spectra range along with the standard deviation.

Table 3.9, The mean C_{50} spectra range in octave-band frequencies along with mid-frequency range averages.

SECTION A									
	Octave-band Frequencies, Hz							Average	
Mean19-338	-1.44	-2.66	-0.86	1.79	2.58	2.79	4.12	0.46	1.17
Mean 14-105	1.38	4.21	3.80	4.89	5.94	6.43	7.86	4.34	4.66
Mean 07-121	3.04	2.81	3.41	5.40	5.47	5.95	7.55	4.46	4.76
Mean 24-115	3.23	5.11	4.40	6.69	7.69	8.59	10.61	5.54	6.38
Mean 24-236	4.77	3.91	3.94	5.46	6.11	6.22	8.21	4.76	5.17
SECTION B									
Minimum	-1.44	-2.66	-0.86	1.79	2.58	2.79	4.12	0.46	1.17
Mean	2.19	2.67	2.94	4.84	5.56	6.00	7.67	3.80	4.46
Maximum	4.77	5.11	4.40	6.69	7.69	8.59	10.61	5.54	6.38
STD	2.11	2.76	1.93	1.64	1.66	1.86	2.08	1.77	1.72

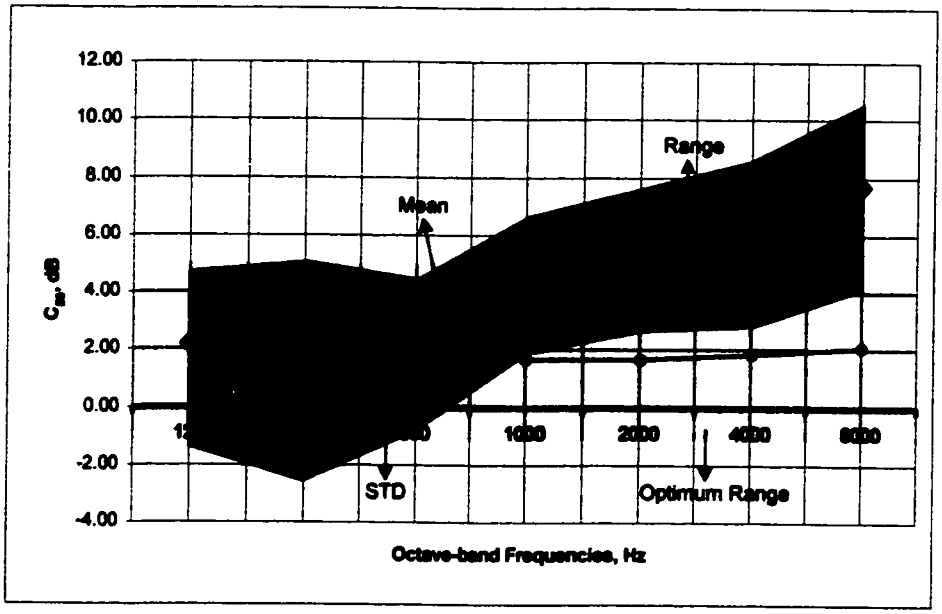


Figure 3.14. C_{50} spectra range along with its standard deviation.

3.5.2 Background Noise (BN)

Analysis of the BN in the sample classrooms suggests the presence of high level noise generated by HVAC systems and other intruded noise. Section A of Table 3.10 describes the mean values of the noise spectra in octave band frequencies measured in all sample classrooms. Mid-frequency average 500-1000 Hz and 500-2000 Hz are also illustrated along with the A-weighted sound pressure level, linear noise level and its noise criterion (NC) rating. Section B of the same table illustrates the overall minimum, mean, maximum and standard deviation (STD) of the BN measured in all the sample classrooms. The overall mean spectrum suggests an overall NC rating of 40 with an A-weighted sound level of 44 dB which is higher than the recommended A-weighted BN level of 35 dB for classrooms of similar volume. The noise range and its mean are shown graphically in Figure 3.15 superimposed over the NC rating curves. The measurement results imply a high noise level rating with a minimum of NC-35 and a maximum of NC-45 with an average of NC-40 rating. The average ranking is much higher than the recommended range of NC-25 to NC-35 for classrooms [1,54].

The RC Mark II ratings of the mean BN spectrum measured in all samples depict similar ratings as NC. However additional sound quality assessment portrays high frequency dominance in two of the classrooms associated with a marginally problematic 'hiss' as shown in Table 3.11. The remaining three classrooms have a 'neutral' rating in terms of frequency dominance with two of the classrooms having an acceptable occupant evaluation (probable) while one of them is marginally acceptable.

Table 3.10. ***Mean BN spectra measured in all the sample classrooms and the average at mid- frequencies.***

SECTION A													
	Octave-band Frequencies, Hz									**Average**			
[illegible]	60.2	56.7	48.5	42.5	41.4	41.3	36.0	28.3	22.6	41.3	[illegible]		[illegible]
[illegible]	63.7	60.3	55.4	45.1	44.4	43.8	39.5	32.2	23.7	44.1	[illegible]		[illegible]
[illegible]	63.5	58.9	50.8	45.4	42.2	37.0	32.0	28.1	23.9	[illegible]	37.1		[illegible]
[illegible]	57.8	52.5	49.0	47.9	44.0	38.3	31.2	25.3	23.3	41.2	[illegible]		[illegible]
[illegible]	59.6	52.8	43.6	40.5	36.9	29.2	25.7	23.1	23.0	33.1	[illegible]		[illegible]
SECTION B													
Minimum	57.8	52.5	43.6	40.5	36.9	29.2	25.7	23.1	22.6	33.1	[illegible]		[illegible]
Mean	61.0	56.2	49.5	44.3	41.8	37.9	32.9	27.4	23.3	[illegible]	37.6		[illegible]
Maximum	63.7	60.3	55.4	47.9	44.4	43.8	39.5	32.2	23.9	44.1	42.6		[illegible]
STD	2.3	3.2	3.8	2.5	2.7	5.0	4.7	3.1	0.5	3.7	[illegible]		[illegible]

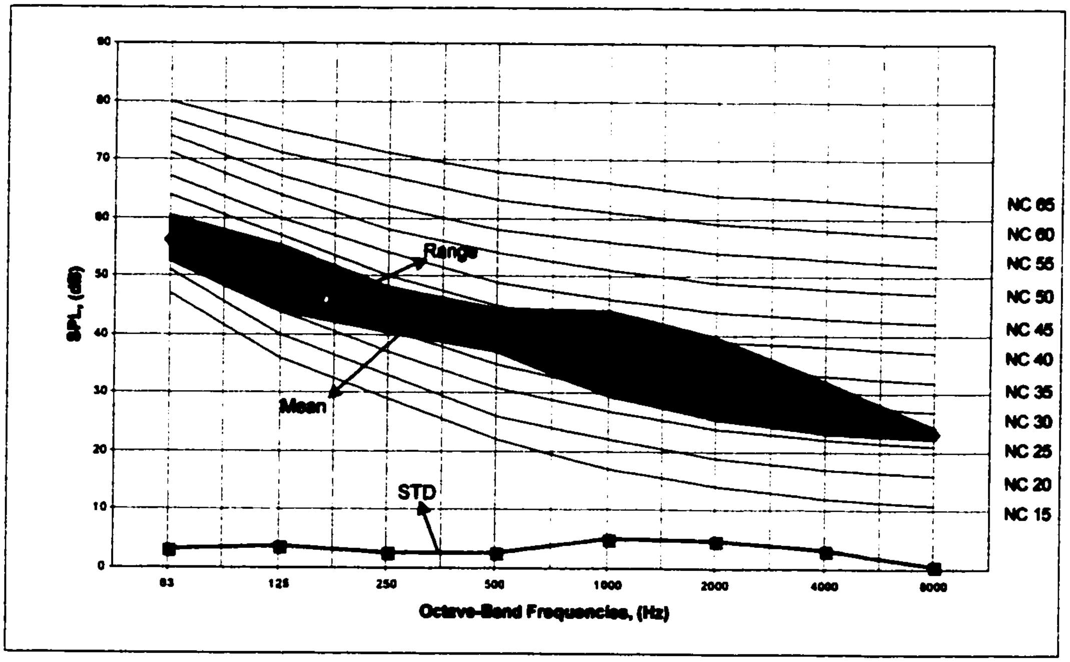


Figure 3.15. BN spectral range plotted over NC curves.

Table 3.11. The RC Mark II ratings of the average BN spectra measured in all sample classrooms.

Room Reference	dB(A)	dB(Linear)	NC	Rating	Sound Quality	Probable Occupant Evaluation
[illegible]	44.9	64.4	45	RC 45 (HF)	High frequency dominant (Hiss)	Marginal
14-106	48.2	68.0	45	RC 45 (HF)	High frequency dominant (Hiss)	Marginal
07-121	43.9	67.1	40	RC 40 (N)	Neutral (Bland)	Marginal
24-116	45.3	62.0	40	RC 40 (N)	Neutral (Bland)	Acceptable
24-226	38.1	63.5	35	RC 35 (N)	Neutral (Bland)	Acceptable

3.5.3 STI and RASTI Measurements

The STI and RASTI measurements of the five sample classrooms were evaluated to highlight the SI characteristics. Figure 3.16 shows the minimum and maximum STI and RASTI range in the sample classrooms with their mean. Their respective SI goodness in the form of STI rating was also defined. The results advocate a large range of STI and RASTI in classroom 14-105 while the range is least in classroom 19-336. Room 24-236 has a better rating with most of its measured locations having a good rating (0.6–0.75). However, there are still some locations with a fair rating as well suggesting a non-uniform SI within this space. Shorter STI and RASTI ratings in room 19-336 have a fair rating but at the same time portray uniformity of the rating throughout the classroom. The RASTI values are as expected higher than their respective STI values, which is obviously due to the less accurate and simplified nature of RASTI measurements compared to STI. Measured STI ratings are therefore used to characterize the SI of the classrooms.

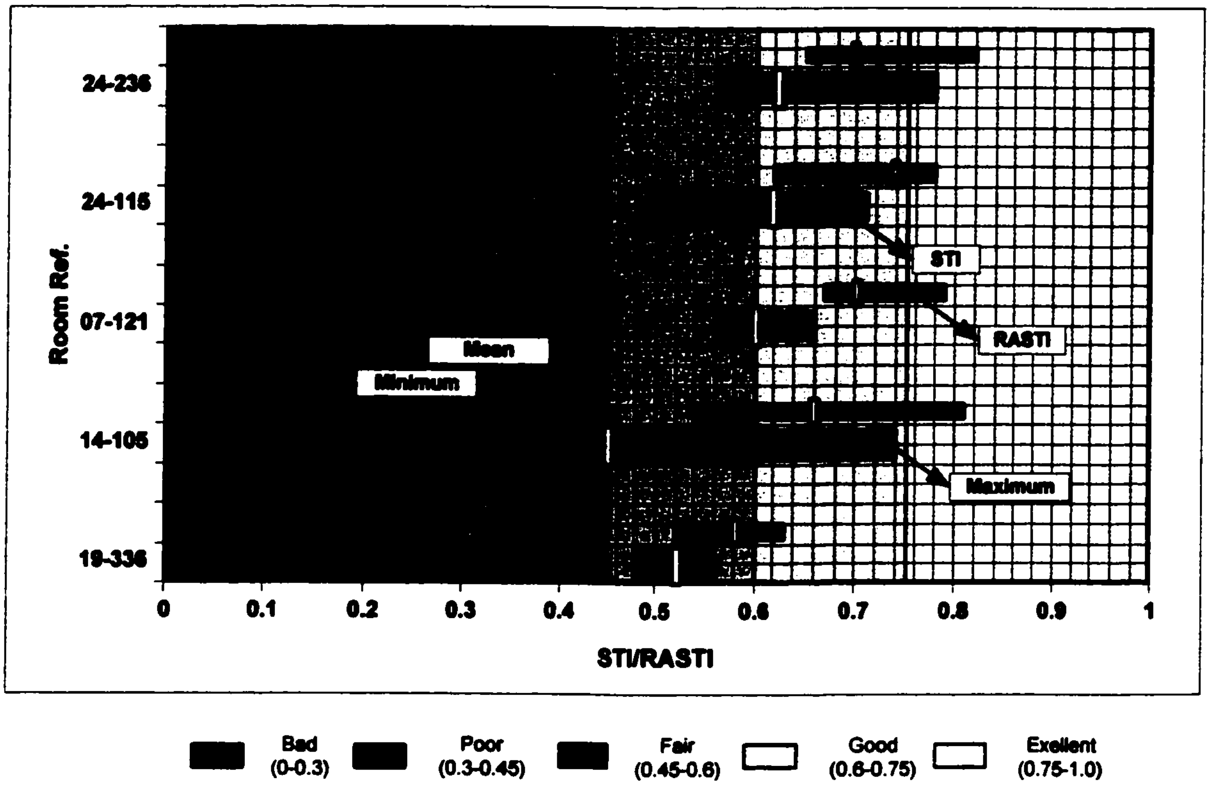


Figure 3.16. STI and RASTI range in the sample classrooms highlighting the minimum, mean and maximum values along with their respective rating.

3.6 Trend Assessment

In this section, the overall average values of the SI indicators measured in all five sample classrooms within the frequency range of interest, that is 500 to 1000 Hz as illustrated in Table 3.12, are compared to infer the trend variation between the parameters. Figure 3.17 compares mean RT_{30} with C_{50} results averaged at the mid frequency range of 500 to 1000 Hz. The trend between these indicators suggests the dependence of C_{50} on RT_{30}. As RT increases, C_{50} values diminish. A similar trend is revealed in Figure 3.18, which correlates RT_{30} average values with the same of D_{50}, STI and RASTI. The inverse dependence is reiterated with reduction in D_{50}, STI and RASTI values as RT_{30} increases. The effect of background noise on SI is depicted in Figure 3.19, which compares noise levels with STI and RASTI values. The STI and RASTI ratings decrease as the noise in the classroom increases. Therefore it is essential to strike a balance between RT_{30}, C_{50} or D_{50} and background noise to achieve a better STI rating and hence improved SI.

Table 3.12. Mean values of mid-frequency (500-1000 Hz) of all the measured indicators.

		Mean19- 336	Mean 14-105	Mean 07-121	Mean 24-115	Mean 24-236
Reverberance	RT-30dB [s]	1.13	0.62	0.71	0.54	0.66
Background Noise	Noise [dB]	41.3	44.1	39.6	41.7	33.1
	dB(A)	44.9	48.2	43.9	45.3	38.1
	dB(Flat)	64.4	68	67.1	62	63.5
	NC	45	45	40	40	35
	RC Mark II	45 (HF)	45 (HF)	40 (N)	40 (N)	35 (N)
Sound Clarity	C_{50} [dB]	0.46	4.34	4.40	5.54	4.70
	D_{50} [%]	52.6	72.1	72.5	77.5	73.9
SI	STI	0.52	0.55	0.60	0.62	0.62
	RASTI	0.57	0.66	0.70	0.74	0.70

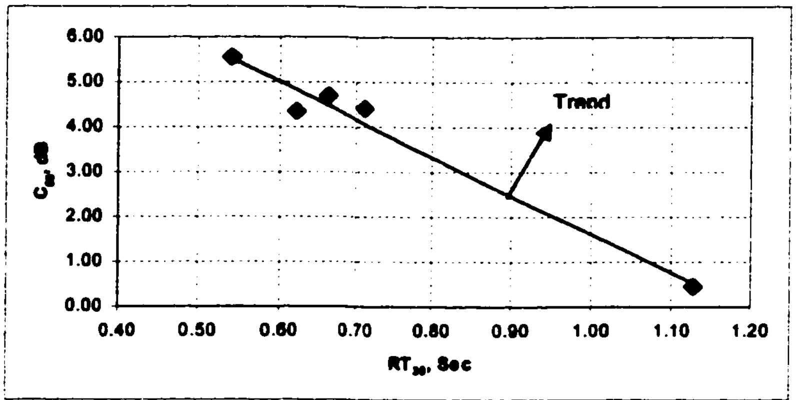


Figure 3.17. Relation of mid-frequency average between the RT_{30} and C_{50} measurements.

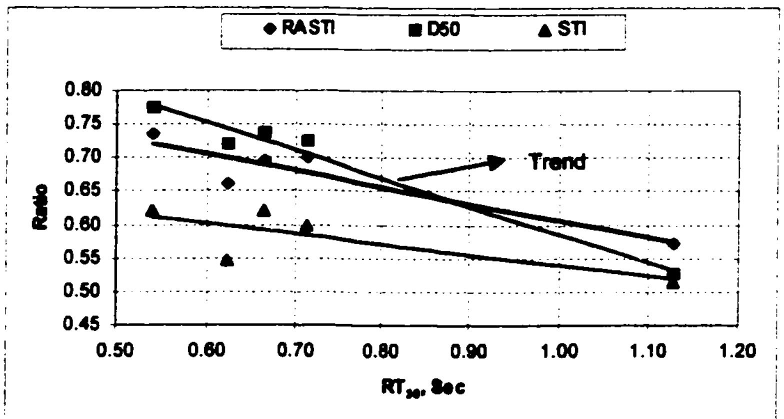


Figure 3.18. Co-relation of mid-frequency average between RT_{30} results versus D_{50}, STI and RASTI results.

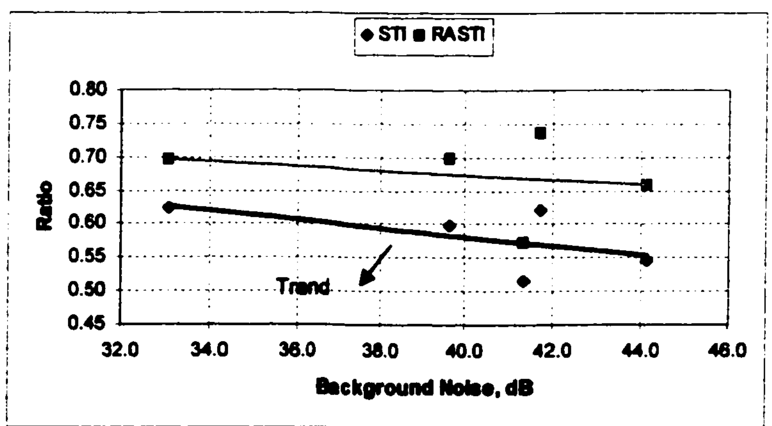


Figure 3.19. Relation between mid-frequency average BN in comparison with STI and RASTI.

3.7 Effect of Instructional Equipment on Background Noise (BN)

Two of the learning spaces selected for measurements were equipped with contemporary educational equipment such as data projector, personal computers, overhead projector and networking equipment. These rooms were deliberately selected to objectively assess the effect of the existing instructional equipment on the BN. Measurements were taken with all the equipment 'on' and later when all the equipment was put 'off'. The architectural and spatial details of these rooms are provided in Table 3.1, with complete documentation attached in Appendix (A).

Table 3.13 illustrates the average spectrum of the BN measured in the classroom referred to as 14-105 with equipment 'OFF' and 'ON'. The average values in various mid frequency ranges are described in the columns on the right of Table 3.13 along with their NC rating. Figure 3.20 depicts the BN range measured in both conditions with their respective mean spectra. The variation in the mean spectrum can be noticed especially in the mid frequency range where most of the speech energy exists. A shift of NC rating from a mean of NC-45 to NC-50 is nevertheless found when the equipment is put 'ON'.

Another classroom, similar to the one described earlier that is referred to as 24-236a, was also measured with all the instructional equipment 'ON' and 'OFF'. Table 3.14 illustrates the spectral average of all the measured points in both conditions along with their respective NC ratings. Figure 3.21 depicts the spectral range as well as the mean spectra in both equipment 'OFF' and equipment 'ON' conditions. With a low existing average BN of NC 30 (when equipment 'OFF'), a considerable shift in background noise is noticed when the equipment is turned 'on' especially in the mid frequency range. A large variation in the average NC rating is seen which shifts higher from NC-30 to NC-40.

The shift in the mean BN spectrum when equipment is 'ON' and 'OFF' is distinct in the second classroom (24-236a) as seen is Figure 3.21, compared to the classroom described first (14-105) due to the presence of high HVAC noise that interfered with the realistic measurements and assessment of instructional equipment generated noise. However, it is clear from both classroom measurements that instructional equipment has an incremental impact on the ambient noise of a classroom when equipment is in operation.

Table 3.13. Mean BN spectrum with instructional equipment 'ON' and 'OFF' measured in classroom 14-105.

Room 14-105: Noise Spectrum Measured With Equipment 'OFF'														
[illegible]														
[illegible]	63.7	60.1	55.1	45.1	44.4	43.8	39.5	32.2	23.7	44.1	42.6		[illegible]	[illegible]
Room 14-105: Noise Spectrum Measured With Equipment 'ON'														
Mean	65.9	61.7	55.6	49.8	47.2	46.7	41.7	34.9	26.6	46.9	45.2		50	[illegible]

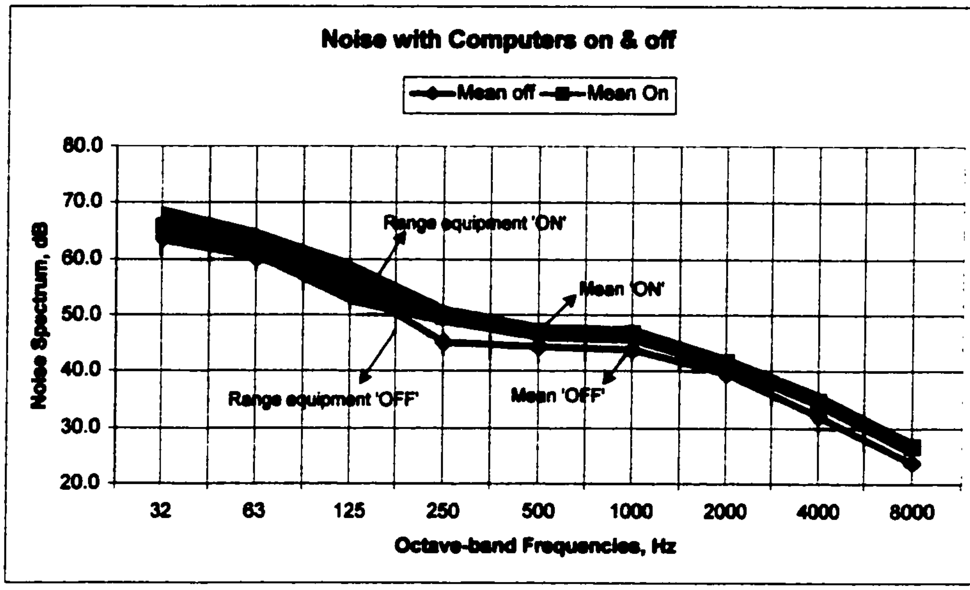


Figure 3.20. BN range measured in room 14-105 with instructional equipment 'OFF' and 'ON' along with the respective mean spectrum

Table 3.14. Mean BN spectrum with instructional equipment 'ON' and 'OFF' in room 24-236a.

Room 24-236a: Noise Spectrum Measured With Equipment 'OFF'														
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	57.7	51.9	46.9	40.1	34.3	29.3	27.1	22.8	22.9	31.5	30.2		[illegible]	[illegible]
Room 24-236a: Noise Spectrum Measured With Equipment 'ON'														
Mean	58.5	53.9	51.4	47.1	43.6	39.3	37.1	36.5	29.0	41.4	40.0		40	40 HF

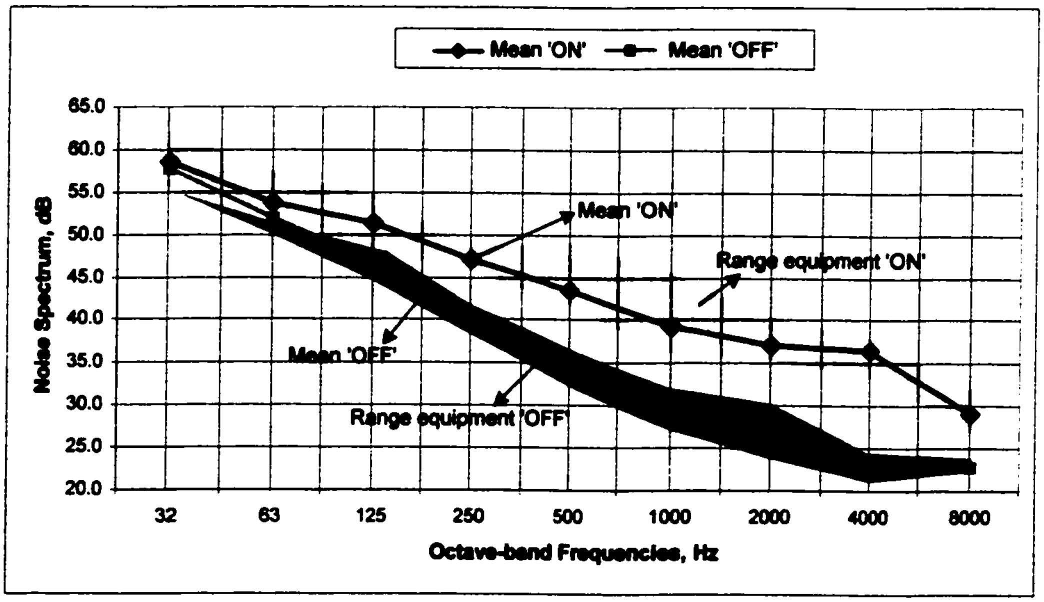


Figure 3.21. The BN range measured in room 24-236a with instructional equipment 'off' and 'on' along with the respective mean spectrum.

3.8 Conclusion of the Measurements

The Analysis of the measurements and the trend variation between the parameters clearly suggests a correlation between the acoustical indicators and room physical characteristics. RT in a classroom is a major parameter, which is a function of classroom enclosure volume and finishing. Depending upon the surface finishing and the proximity of a listener to the room surfaces, RT may vary in a classroom creating zones of non-uniform acoustics. As RT fluctuates all along the classroom, the D_{50} and C_{50} values are in turn affected. Therefore, average values of these indicators in a classroom provide an enhanced evaluation of the indicator trends and can be used to represent the acoustical characteristics of a classroom. The D_{50} and C_{50} have a close proportionality with RT. High RT in a classroom reflects a better D_{50} and C_{50} value, while the optimal value of these indicators can be achieved only under optimal RT conditions. The sample classrooms with optimal average RT values result in clear and distinct listening conditions and hence improved SI.

Ceiling and wall finishes above the listener level have a considerable effect on dictating the room acoustical parameters. As observed from the measurements, most of the university classrooms are finished with reflective walls and ceilings, which result in high RT and sound clarity deficiencies. Absorption panels installed on one of the sample classroom walls (24-115) results in better acoustical performance when compared with other classrooms. The best values of acoustical indicators were found in this classroom while in all other measured classrooms, the values of the same indicators were found to be higher than recommended values. Exaggerated and non-uniform acoustical measurements were noticed in sample classrooms (14-105 and 07-121) due to the presence of a hard reflective floor, which creates multiple reflections between the floor and the existing furniture. Better hearing conditions prevailed in classrooms laid with carpet flooring.

The presence of sound absorbing material on the ceiling yields good sound quality as seen from the measurements of classrooms 19-336 and 07-121. Both of these classrooms have similar wall finishes. However the former had a sound reflecting ceiling and a high RT value while the latter had a sound absorptive ceiling which is responsible for a lower RT value although the same is laid with a sound reflecting hard flooring. Therefore to achieve good SI, it is necessary to provide the optimum quantity of absorptive materials on the classroom surfaces to exploit the benefits of RT for clear and distinct speech comprehension in a university classroom.

SI in a classroom is also directly affected by the BN. A classroom with optimum RT_{30}, D_{50} and C_{50} values could still have a lower STI or RASTI rating due to the presence of high BN within the enclosure. Better RT, D_{50} and C_{50} results are noticed in sample classroom 14-105 in comparison with classroom 07-121. However the latter yields better STI values than the former due to the presence of low BN in this classroom. Thus, to achieve good speech quality in a university classroom, it is essential to contain the BN within acceptable limits.

BN in a university classroom is also affected by internally generated noise. The noise generated by personal computers, printers, data projectors and other instructional equipment has an incremental effect on the existing ambient noise within a classroom. BN measurement results of classroom 14-105 and 24-236 reflect the distinct shift in the NC ratings when the equipment is 'ON' and 'OFF'. The prevailing BN is thus exaggerated and in turn can create noisy and un-intelligible speech conditions in a university classroom unless accounted for. This fact renders a smart classroom highly vulnerable to poor SI as these classrooms are equipped with a large amount of instructional equipment.

SI in a classroom is also influenced by the proximity of a listener to the sound source (instructor), the boundaries of the room and the location of noise sources. A wide range of STI rating suggests non-uniform acoustical conditions in a classroom as seen in the measurements of classroom 14-105, degrading the functionality of a classroom enclosure. A zonal variation of SI characteristics is detrimental for students and has a considerable impact on the comprehension of instructions and lecture in a classroom. Therefore it is essential to achieve a uniform SI rating throughout the classroom. A narrow variation range of STI values would produce similar listening conditions all around the classroom. A classroom with a low STI rating but a narrow variation range is preferable to one with a high STI rating but a wider variation range. The former would result in a uniform SI rating once the classroom physical characteristics are enhanced by acoustical improvement.

The issues described above provide a better understanding of the influencing parameters that affect SI in a classroom and at the same time allow visualization of the impact of instructional equipment generated noise on the ambient noise within a university classroom. These points will further be utilized as guidelines for modeling a typical smart classroom and for assessing the impact of noise generated by instructional equipment on SI in such classrooms.

CHAPTER 4

4.0 MODELING A TYPICAL SMART CLASSROOM

4.1 Introduction

The fact that surface finishes affect the Speech Intelligibility (SI) in classrooms is studied in detail within this section. The aim is to investigate the best placement of sound-absorbing materials with varying absorption potentials especially in the frequency range where speech energy is mostly dominant. SI parameters are compared in various cases of surface absorption characteristics using ODEON computer modeling software. ODEON, as described in section 2.5, allows simulation of the acoustical conditions in rooms using a wide range of sound-absorbing materials with evaluation of sound characteristics facilitated utilizing a number of sound sources and sound receivers.

A model of a typical smart classroom [30] is generated using a CAD software and is exported into ODEON. The model is thoroughly verified for its sound tightness, leakages and its representation of a room enclosure. Simulations are carried out comparing the SI parameters similar to the measurements described in section 3.0 with the model surfaces assigned a variety of percentage sound absorption, which leads to a base case model with ideal percentage absorption on all room surfaces. The results of acoustical measurements in similar existing classrooms described in chapter 3.0, are used to introduce realistic classroom features in terms of the physical conditions and Background Noise (BN). The base case is further modified changing the sound-absorbing elements of different portions of the room surfaces to investigate the effect and finally achieve the best possible configuration of sound-absorbing material placement and absorption characteristics for enhanced SI. The ultimate model which is a result of numerous simulations is compared with ASA recommendations on classroom acoustics [1] and the effect of the noise generated by instructional equipment and the over all ambient noise on SI is studied.

4.2 The Classroom Model: Assumptions and Details

A typical smart classroom model is developed utilizing CAD software, having a simple layout as described earlier in section 2.4. The classroom is assumed to have a simple geometry with an area of 100 m^2. The size is 12 m by 8.4 m with a height of 3.5 m as shown in Figure 4.1. The classroom accommodates 24 student workstations with an average area of 4.2 m^2 per student. Four tables are symmetrically arranged each housing 6 PC's. The simple arrangement allows a further extension of 4 workstations if required by shrinking the gap between two rows of tables and reducing the space between the teacher station and tables. The teacher station occupies the formal central location on the display end of the classroom.

The instructor is equipped with a portable computer at the lectern which houses all display controls including an overhead projector directed towards the display wall. The entire display wall is used as a screen as well as an electronic white board. Storage units for networking equipment, video display equipment, wiring joints, an uninterrupted power supply system etc. are chiseled out at the corners of the display wall for better utilization of these corners and to provide symmetry.

The model generated in CAD using 3D faces is loaded into ODEON and checked for overlapping surfaces and intersection tightness. Active graphical ray tracing is used to confirm the leakages tightness of sound rays. For simplicity of the model to be used by ODEON acoustical evaluation software as required, the tables are represented as full length blocks fronted by blocks on two ends that represent lightly upholstered chairs. Similarly blocks also represent the teacher station. These blocks are hollow blocks made up of surfaces facing the classroom enclosure and having a transparent base. In the same way the corner storage panels are chamfered and formed out of surfaces. Figure 4.2 shows the model as displayed by ODEON in 3D.

The model surfaces are divided into two categories as described in Table 4.1. The first category is of those surfaces that remain constant throughout the simulation. These are the table surfaces, student block, corner panels, door, lintel and the front wall display area. The floor is taken as a hard floor in the first run, but is changed to light weight carpet and kept constant throughout the later simulations. The second category is of those surfaces that are modified and the effect of each modification is analyzed. These constitute the three wall surfaces and the ceiling of the classroom enclosure.

The model is simulated under a constant BN corresponding to NC 30 rating. A BN range of NC 25 to NC 35 is recommended in the literature. However a BN of NC 30 is selected to represent an average of the recommendations and at the same time reflects the BN characteristics of the quietest classroom measured (Chapter 3). To verify the reverberation characteristics of the space, an omni directional sound source is located at the instructor location at a height of 1.75 m, which is the average height of a person.

For measuring other SI indicators, a directional sound source that mimics instructor speech (talk raised) is added at the same instructor location. The simulation is carried out with one source activated at a time. Nine receivers are distributed throughout the classroom workstations representing critical points in the space as shown in Figure 4.3. Figures 4.4(a) and 4.4(b) display the interior rendered views of the model generated by ODEON clearly defining the classroom geometry.

The simple and symmetrical layout of the classroom allows us to analyze the SI features in a better manner with nine receiver positions highlighting the acoustical distribution throughout the space. The model is however free of window openings for two reasons: firstly for simplification as required by the ODEON software and secondly due to the specialized nature of these classrooms, windows are omitted as they would both affect display and as be a source of glare due to reflections from computer monitors.

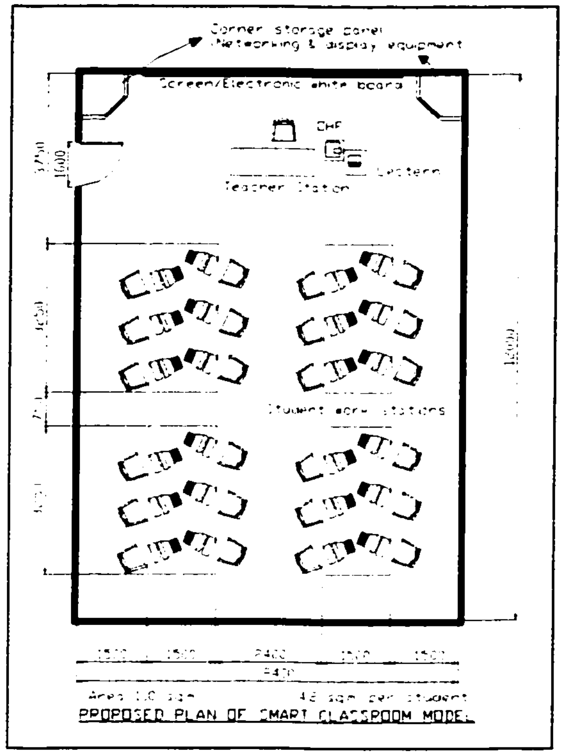


Figure 4.1. Plan of the smart classroom model.

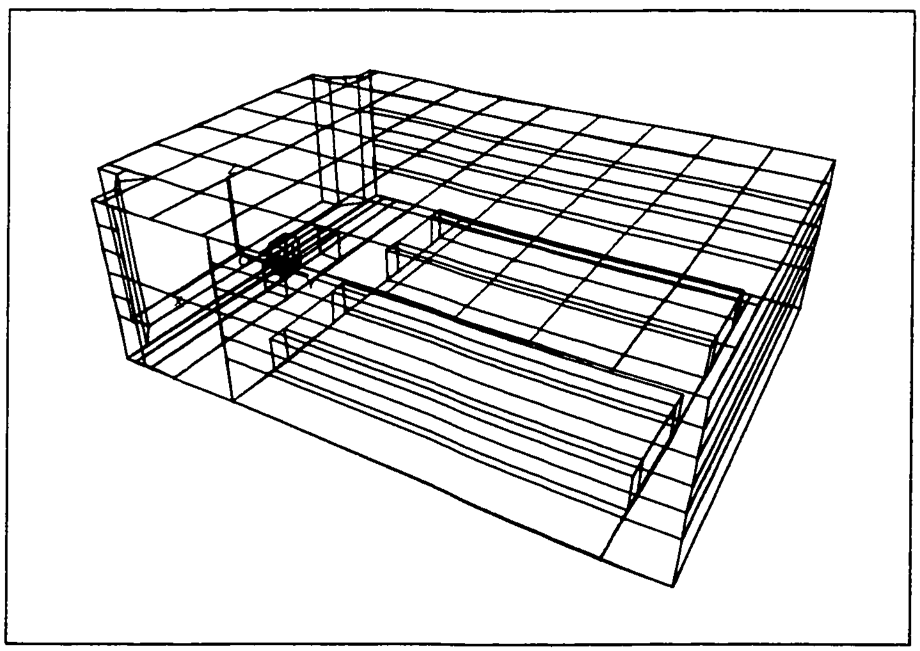
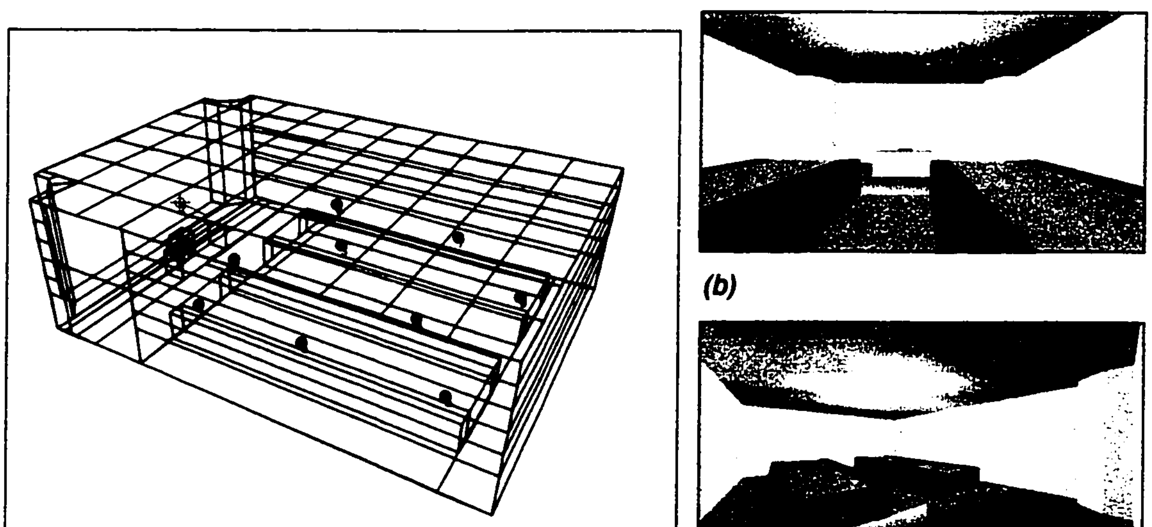


Figure 4.2. 3D View of the smart classroom model as displayed by ODEON.

Table 4.1. Details of the constant and variable surfaces of the classroom model.

Room Surface	Category	Details
Table	Constant	Hard wood polished (ODEON ref. # 603)
Occupant seats	Constant	Lightly upholstered seats (un-occupied) (ODEON ref. # 906)
Door/Lintel	Constant	Hard wood (ODEON ref. # 603)
Corner panels	Constant	Hard wood (ODEON ref. # 603)
Front wall	Constant	10% absorption
Floor (case 0), only	Variant	Hard floor (ODEON ref. # 2018)
Floor (case 1 – 9)	Constant	Light weight carpet (ODEON ref. # 506)
Lower 1.0 m portion of the walls	Constant	10% absorption
Side & back wall	Variant	10 % to 90 % absorption
Ceiling	Variant	10 % to 90 % absorption



(a) *(b)* *(c)*

Figure 4.3. *(a) Location of the sound sources and 9 receivers in the classroom model. (b) and (c) rendered interior views of the classroom model.*

4.3 The Simulation Steps

The classroom model is initially simulated in ten steps (cases) to examine the SI parameters within the modeled classroom. During these simulations, the fixed surfaces are kept constant as discussed earlier: the floor specified as hard floor and the variable surfaces i.e. walls and ceiling is allocated absorption of 10% with a scattering of 10%. To represent irregularities due to the PC's and other equipment on the table, the table surface is assigned a scattering of 30% and is kept constant throughout the simulation runs. The simulation cases with variable sound absorption features are described below in Table 4.2.

Table 4.2. Sound-absorbing material features of the simulation cases.

CASE #	FLOOR ABSORP. %	WALL ABSORP. %	CEILING ABSORP. %
0	Hard floor (ref. 2018)	10	10
1	Carpet floor (ref. 506)	10	10
2	Carpet floor (ref. 506)	20	20
3	Carpet floor (ref. 506)	30	30
4	Carpet floor (ref. 506)	40	40
5	Carpet floor (ref. 506)	50	50
6	Carpet floor (ref. 506)	60	60
7	Carpet floor (ref. 506)	70	70
8	Carpet floor (ref. 506)	80	80
9	Carpet floor (ref. 506)	90	90

4.3.1 Acoustical Verification of the Model

Before going ahead with the simulation, it is essential to verify the classroom model for its exact representation of a typical room enclosure. For this purpose a separate simulation is carried out using the Case '0' configuration as described in Table 4.2 with an omni directional sound source placed at the instructor location (i.e. at the center of the room and 1.5 m from the display wall). Four receivers are allocated along the same axis as shown in Figure 4.5, at a height that mimics human ear in sitting conditions (1.2 m). The gain of the source is set to 31dB. In this case, the value of Sound Pressure Level (SPL) equalizes the value of Strength (G) which is the total level in reference to the level the point source produces at 10 m in free field as defined in IS-3382 [56].

Figure 4.6 shows the RT calculated by averaging 500 Hz to 2KHz octave bands in this simulation along with the distance from source. All the calculations are based on averaging 500 Hz to 2 KHz octave bands, as most of the speech energy is dominant in these frequency bands. The variation in RT is noticed all along the central axis.

Figure 4.7 displays the SPL along the axial line, which also corresponds to the G value as described earlier. As the distance from the sound source increases, a decrease in SPL is noticed. The decrement is less than 3 dB at a distance of 2 m from the source and this keeps on decreasing till a distance of 7 m, beyond which slight increment is noticed. This emphasizes the reverberance characteristics of the enclosure similar to a realistic room with RT of around 1.1 sec at the center of the room, which is much higher than the optimum value for classrooms.

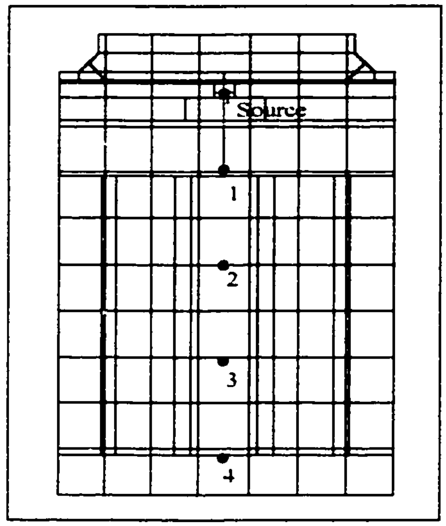


Figure 4.4. Plan depicting the axial placement of 4 receivers for reverberation assessment.

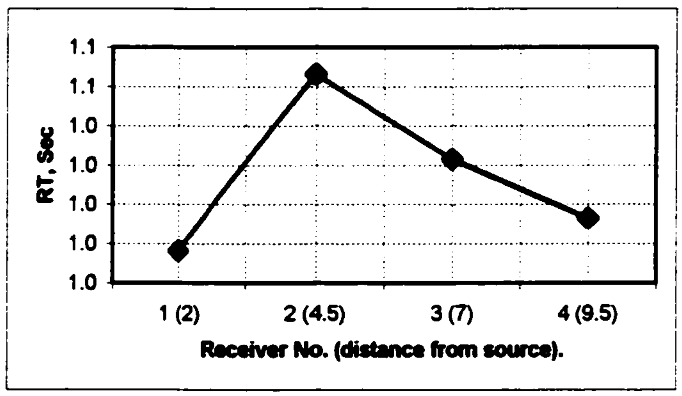


Figure 4.5. RT_{30} at 4-receiver locations and their distance from sound source.

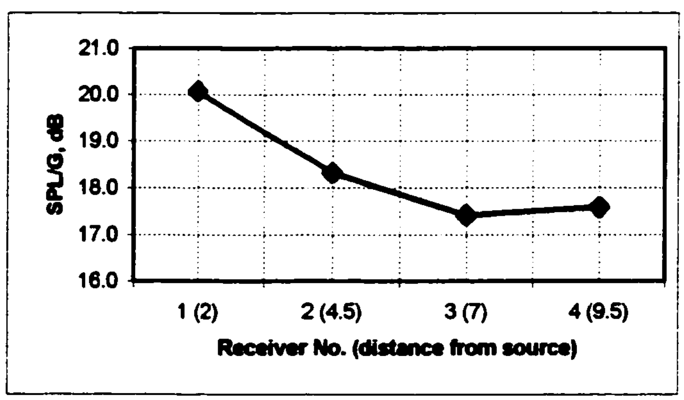


Figure 4.6. The SPL decreases as the distance from the sound source increases.

4.4 STEP 1: Effect of Changing Sound Absorption Percentage on Speech Intelligibility (SI)

The absorption characteristics of surfaces directly affect the RT in the rooms. As the percentage absorption of variable surfaces is increased, the RT decreases. However variation in the slope of RT values from case to case is noticed and tends to decrease. Figure 4.8 shows the RT calculated in all 10 cases by ideal diffusion assumptions as well as the average of 9 receivers within an average of 500 Hz to 2 kHz. The curves generated from the results using these different methods all suggest the same. As the floor is changed from hard floor to carpeted floor, the RT is effectively reduced. The effectiveness of RT reduces as more absorptive walls and ceiling tiles are used and in the later cases the effect on RT is almost negligible. Therefore the influence of absorption materials of walls and ceiling has a cutoff point beyond which the outcome will not be greater in comparison to the improvements in SI as well as financial inputs.

Increasing the absorption percentage has a similar bearing on SPL. As shown in Figure 4.9, a decrease in SPL is noticed and the slope reduces as the percentage absorption is increased. This again suggests that the SPL does not reduce linearly by increasing the quantum of absorption and has a limit of maximum influence beyond which addition of absorption is less efficient.

To further investigate the effect of absorption characteristics on SI, evaluation of SI indicators calculated by simulating the model using a directional sound source that mimics human speech is followed. A Talk Raised sound source with a built in directivity and pressure spectrum is used with an impulse length of 2.2 seconds. The average STI increases as the percentage absorption increases with its efficiency decreasing as the absorption quantum increases. Figure 4.10 depicts the average STI values increasing from fair to excellent with a decreasing slope between each case. The variation in the slope of the first 3 cases and the remaining cases suggests a reduced effect on SI efficiency as the absorption increases 30 percent. Thus case 3 has a maximum effective absorption quantum beyond which the influence of increasing absorption is negligible.

For a detailed survey of SI at student or occupant station, an analysis of multipoint response at the 9 receivers distributed in the classroom model is studied. The SPL (A-weighted) as shown in figure 4.11 for 9 receiver location displays a reduction of SPL(A) with increasing absorption from case 0 to case 9. In initial cases, the SPL(A) is consistent for all receiver locations but with the increase in absorption percentage, the SPL(A) decreases as we move farther away from the sound source. It is evident that case 3 represents the average of all the curves and, beyond this point, the reduction in SPL(A) slope with distance begins to fall.

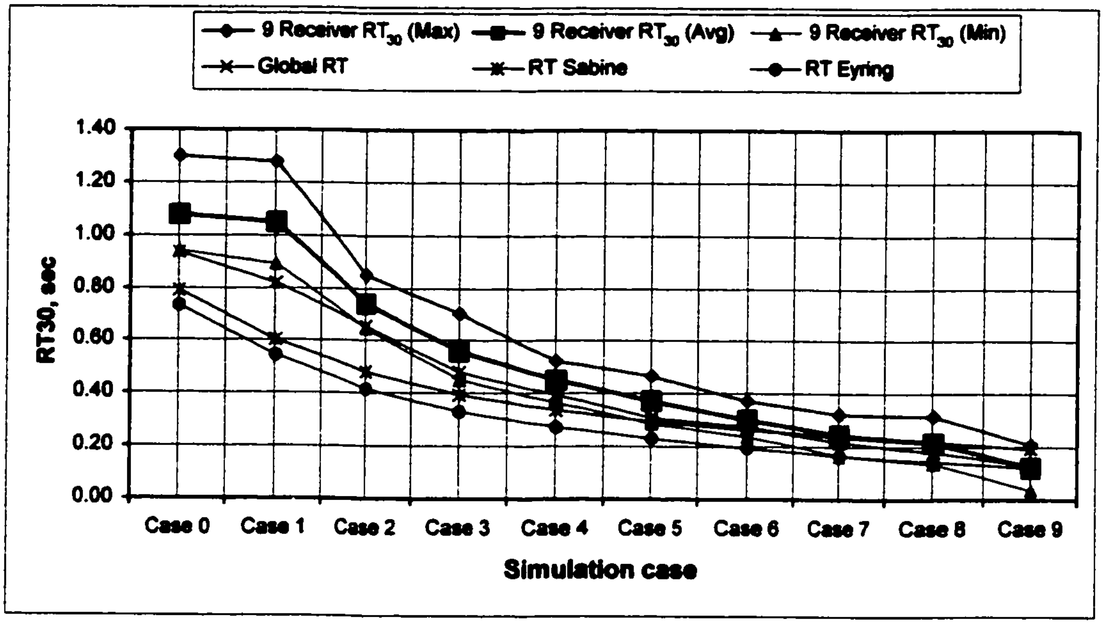


Figure 4.7. *RT_{30} at various cases using diffused theory calculations and average of 9 receivers.*

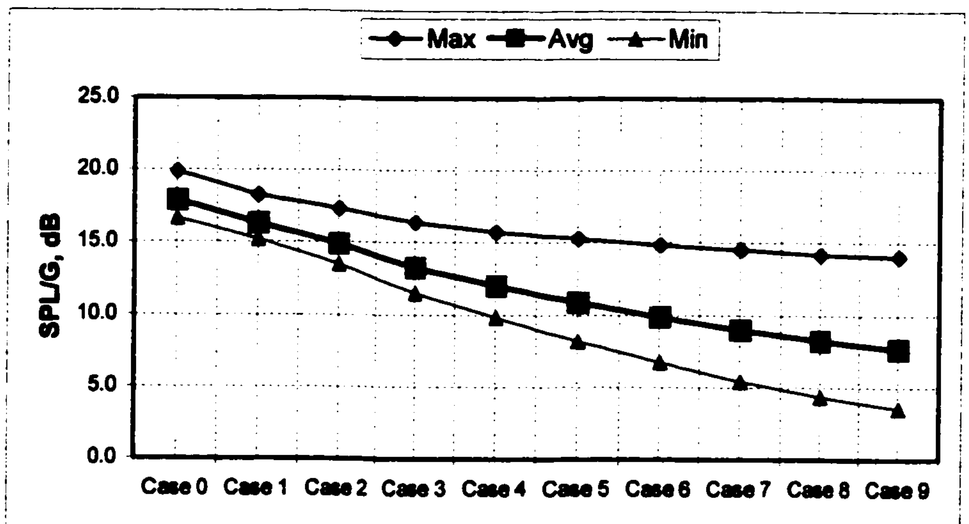


Figure 4.8. SPL variations among the various cases.

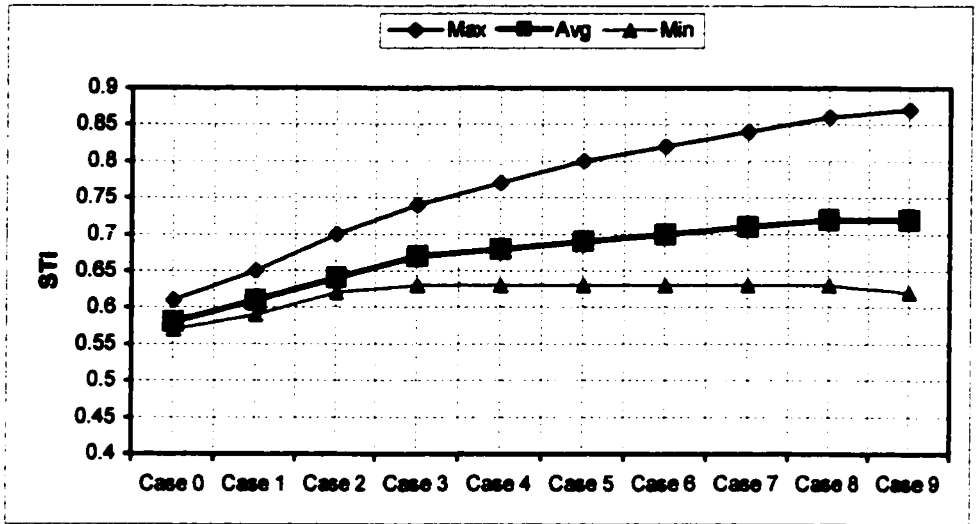


Figure 4.9. Variation in STI with the increase in absorption percentage.

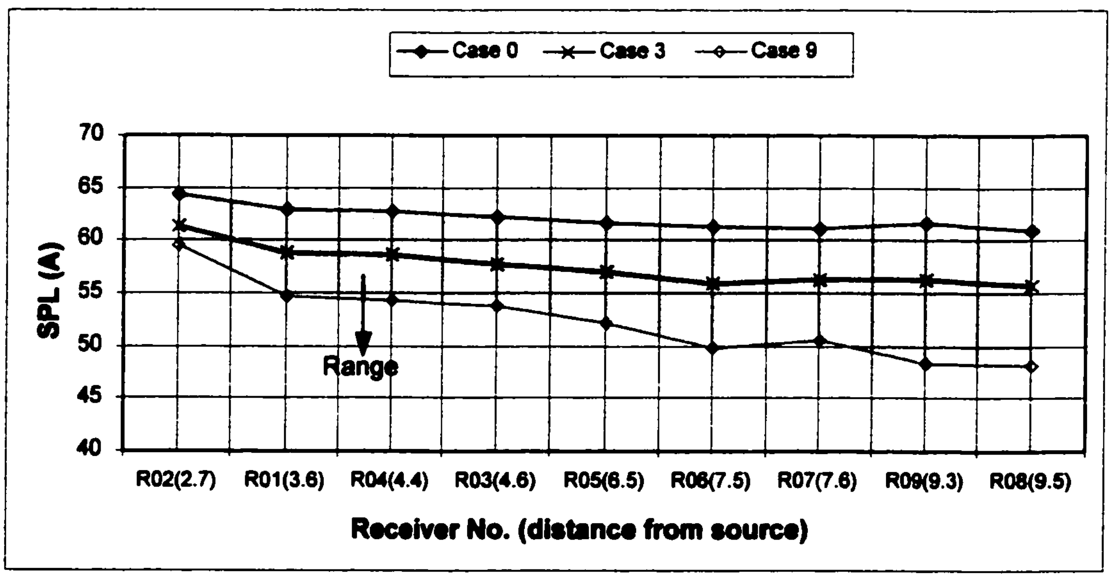


Figure 4.10. Range of SPL (A) at the 9 receiver locations in the 10 simulation cases.

Similar results are noticed when comparing the STI at various receiver locations with the absorption percentage increase cases as shown in figure 4.12. As the absorption quantum increases, the STI improves with its effectiveness decreasing beyond case 3. The STI is consistent in the first four cases after which the improvement in STI values starts to deplete with distance, again symptomatic of case 3 as the ideal absorption proportion. Furthermore, the values of Clarity at 50 m.sec (C_{50}) are calculated from RT_{30} at each receiver location. As shown in Figure 4.13, the results support the above argument showing the average optimum value of C_{50} at case 3 absorption characteristics. Therefore case number 3, having absorption of 30 percent for wall and ceiling is an ideal base case for further modeling of the computer classroom.

Figure 4.14 compares RT_{30}, D_{50} and STI ranges calculated at all nine user locations in the ten simulation cases. An intersecting region of these ranges is found to correspond to the best case with all of the parameters within their respective recommended ranges but beyond this zone, the SI characteristics seem to have a low response to increasing percentage sound absorption. This region again falls within a sound absorption of case '3', which is allocated absorption of 30 percent to its varying surfaces. Therefore, case '3' is selected as the ideal base case for further investigation of the best absorption material placement and percentage absorption quantum, for improved SI.

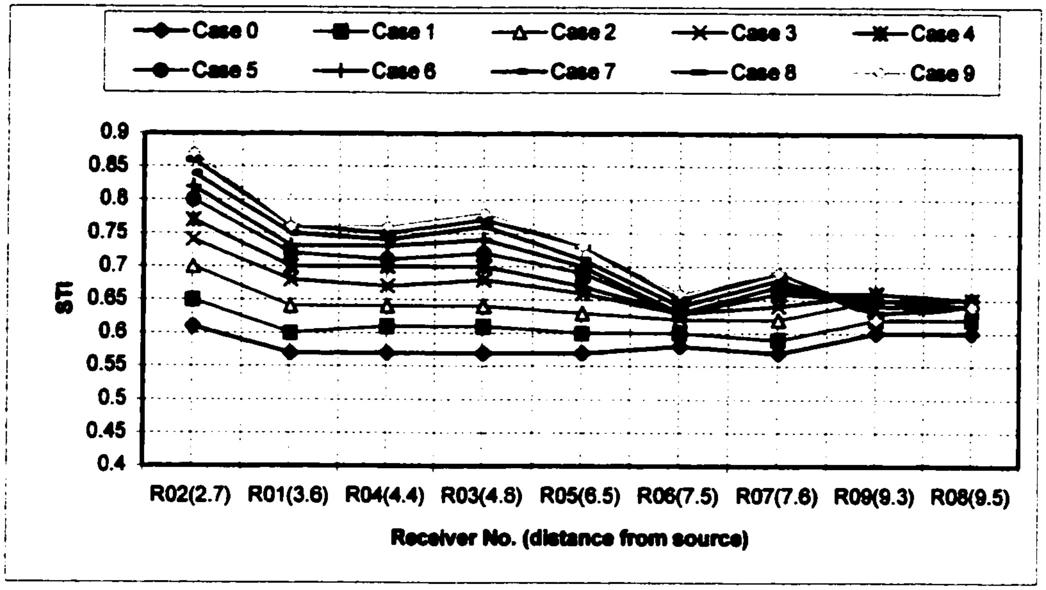


Figure 4.11. STI values at various receiver positions in the 10 simulated cases.

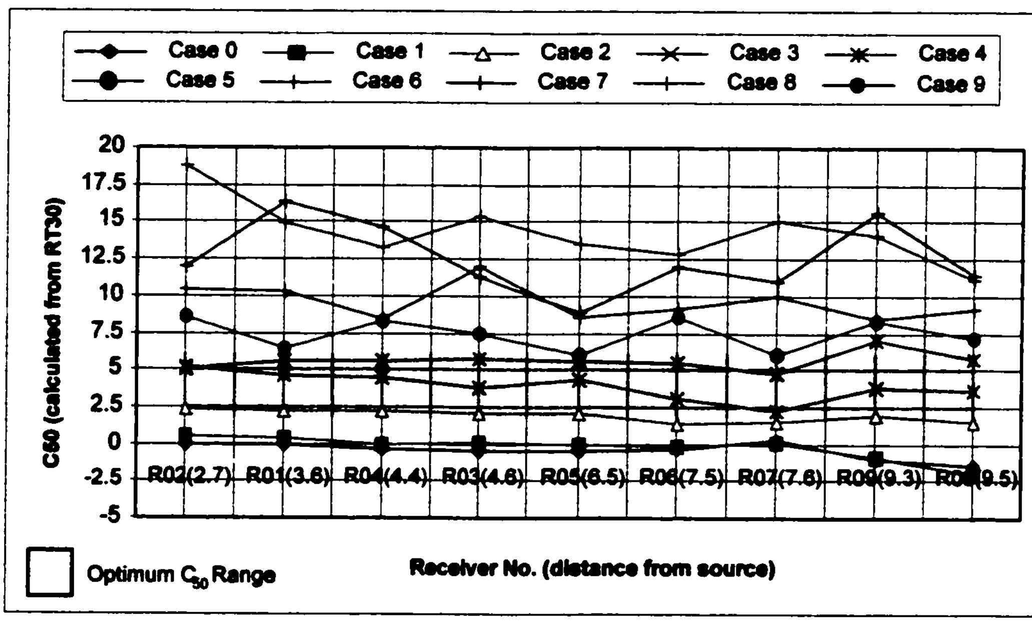


Figure 4.12. C_{50} values at 9-receiver locations in all the 10 simulation cases.

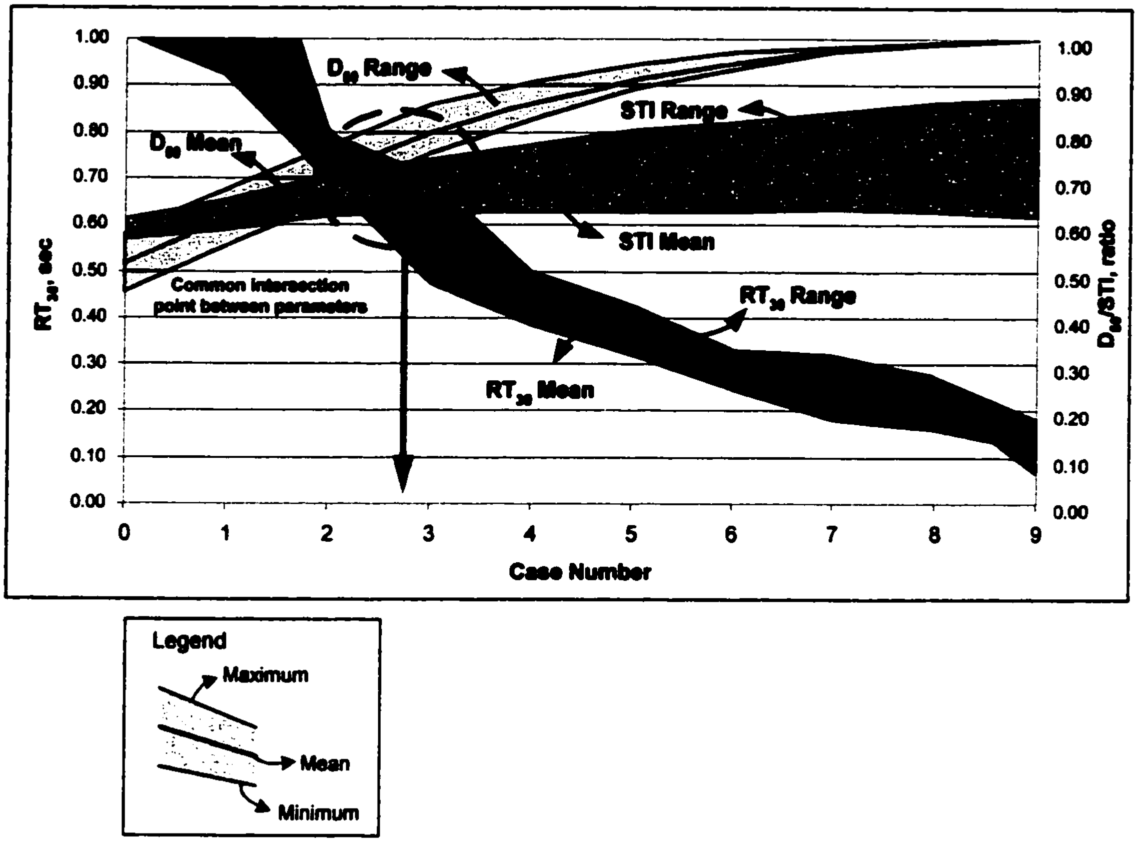


Figure 4.13. *Comparison of the RT_{30}, D_{50} and STI value range. The intersecting zone of these parametric ranges is within the acceptable range of all these SI indicators and correspond to the Case '3' absorption percentage.*

4.5 STEP 2: Investigation of Sound-Absorbing Material Placement on Modeled Classroom Ceiling

The base case described earlier is found to be the best case with all the SI parameters within their respective recommended ranges. Therefore, this case with all its variant surfaces (Table 4.2) allocated percentage absorption of 30% is further simulated, varying the different portions of the ceiling in terms of the placement and properties of absorption material, and comparing the SI parameters in detail. The objective is to achieve the best possible layout of sound-absorbing material placement that enhances the SI characteristics of the simulated classroom as described in the literature as well [1,54,60].

Numbers of simulations are carried out in a systematic manner with different ceiling patterns as well as quantum of percentage absorption. The walls are however maintained at a constant sound absorption level of 30% of the base case. This allows better visualization of the change in the SI indicators leading to the identification of the best overall results. As a large amount of data is calculated from numerous simulations, only the mile-stone cases with major parametric changes are described to facilitate the procedural understanding and at the same time limit the number of graphical outputs.

The base case with 30 percent absorption on all variant surfaces is found to have an RT_{30} value range of 0.5 sec to 0.75 sec, with a 'GOOD' STI rating. The mean RT_{30} value of 0.58 sec is noticed with most of this range exceeding the optimum limits of 0.6 sec as highlighted in the literature [54], while C_{50} ranges from 4.1 dB to 6.7 dB with a mean value of 5.0 dB as shown in Figure 4.15 (Case 1). As the absorption percentage of the whole ceiling is increased to 40% keeping the wall constant as 30% absorption, the RT_{30} range is found to reduce with a shift in the average RT_{30} to a lower value. The STI range increases with no effect on the average STI value and a similar pattern is noticed with C_{50} values.

Considering the impact of the sound absorption quantum and its placement on the SI indicators at the nine receiver locations already assigned, the ceiling layout is modified and simulated. Different percentage absorption is allocated to the ceiling dividing it into various zones. Here again the results from the nine receivers guide the next ceiling modification. Increasing the ceiling absorption over the instructor area is found to shift the average RT_{30} to a higher value with no change noticed in the RT_{30} and STI range with a slight shift noticed in the C_{50} range. These results reiterate the fact that increasing the ceiling absorption percentage over the student station zones results in the reduction of RT_{30} below required levels disallowing exploitation of beneficial sound reflections.

The reduction of ceiling percentage absorption over the receiver location improves the RT_{30} and C_{50} values at the central areas of the classroom while the receiver locations nearer to the walls are found to have higher RT_{30} values. Therefore to contain the RT_{30} of these locations, more absorption quantum is provided on the ceiling near the walls forming a ring around the periphery of the room as shown in Figure 4.15 (Case 3). The improved performance of this configuration is also validated in the ASA review on classroom acoustics [1].

Simulation Case 3 of Figure 4.15 depicts a peripheral ring of 50% absorption along the walls of the ceiling and over the instructor area. The central portion of the ceiling is provided with an absorption percentage of 40%. The results show reduction of RT_{30} range with a shift in RT_{30} average value to a lower value. Narrower range of SI indicators implies an even distribution of acoustical parameters throughout the classroom and hence better SI. No change in the STI values is noticed in comparison to the earlier case. However the C_{50} range increases and shifts to a higher value.

The absorption percentage of the ceiling central portion over the listener locations is further reduced to 30 percent and then to 20 percent. Simulations results in these cases showing an increase in the RT_{30} range with most of the range beyond the optimal limits. Nevertheless a reduced range of STI and C_{50} is found depicting an improvement in SI at the central locations.

The possibility of more enhancements is thus evident. Figure 4.15 (Case 4) shows the result of simulation with the ceiling peripheral ring having an absorption percentage of 50% and the central portion assigned a with 20% absorption level.

The results of SI indicators at the receiver locations in the center of the classroom reveal low SPL and RT_{30} values. To improve the RT at these locations, the ceiling over the central portion of the room is assigned a highly reflective ceiling with sound absorption percentage of 10% and the peripheral ring of the ceiling is maintained with an absorption of 50%, the same as in Case 4. As shown in Figure in 4.15 (Case 5), the RT_{30} range is increased in comparison with the earlier case. However no change in the mean value of the RT_{30} or STI & C_{50} ranges is noticed. The increase in the RT range is due to higher RT_{30} values at locations near the wall surfaces but changing the percentage absorption of the wall surfaces can control RT at these receiver positions. The main concern at this point is the central area of the classroom, the acoustics of which are enhanced by providing reflective ceiling over this area.

Improvements in RT_{30}, C_{50} and STI values are found in Case 6 as shown in Figure 4.15 (Case 6). When another row of ceiling tiles is placed over the instructor area is allocated percentage absorption of 10%. This proves that a reflective ceiling over the central portion of the classroom right in front till the edge of the instructor location improves the SI parameters. However, simulations conducted with reflective ceiling assigned over the whole of the instructor area as recommended by the ASA review on classroom acoustics [1], results in un-balanced RT_{30} and C_{50} associated with longer value ranges. In this case, the shortest RT_{30} range with a shift of the overall value range along with the mean, to a lower value is noticed. In addition to having a narrow STI range the values are also improved. Similar results are depicted with the C_{50} values. Therefore the Case 6 configuration presents the best results among all the simulation runs conducted so far for ceiling optimization.

The percentage absorption on the ceiling periphery is again increased in Case 7 as displayed in Figure 4.15 to verify the impact of providing additional absorption along the ceiling periphery on RT_{30} values of the receivers located near the wall. Absorption of 60% is assigned to the ceiling ring surrounding the walls with 10% absorption on the central area of the ceiling in the same configuration as Case 6. The range of all the SI indicators is found to increase with very minor improvements at certain receiver locations. This proves that Case 6 is the best configuration of sound-absorbing material in the modeled classroom and a further increase of ceiling absorption percentage has a minimal effect on improving SI in the smart classroom. Therefore Case 6 ceiling configuration is selected for the next set of simulations.

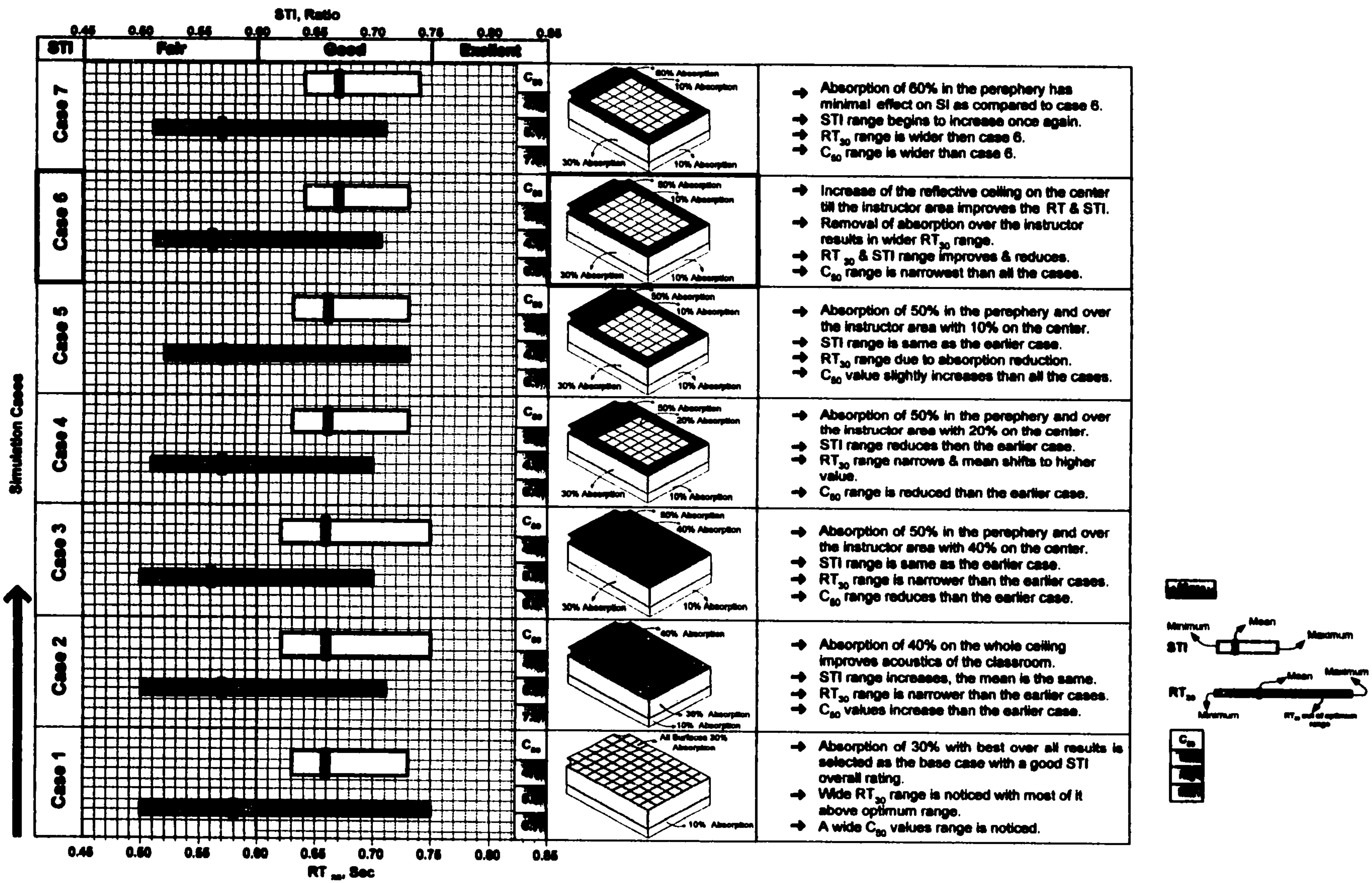


Figure 4.14. ***Investigation of the best overall placement of acoustical absorption material in a typical smart classroom: Ceiling investigation***

4.6 STEP 3: Investigation of Sound-Absorbing Material Placement on Modeled Smart Classroom Walls

The best ceiling absorption configuration achieved in the second set of simulations in Section 4.5 is selected as the base case and the sound absorption properties of bands along the walls are changed to verify the impact of absorption positioning and absorption quantum on SI. The aim is to evaluate the best possible ceiling and wall sound absorption percentage and layout that would result in better SI under the assigned BN conditions of NC 35 rating. As described earlier, Case 6 of Figure 4.15 is the best ceiling configuration obtained from simulations with all the three walls having a constant absorption percentage of 30%, the ceiling peripheral ring allocated 50 percent absorption and a reflective central portion of 10% sound absorption. This case is selected as a base case and further simulations are carried out varying the location of sound absorption percentage and placement along the walls. Ultimately, the best overall configuration of ceiling and wall absorption material placement is identified with the SI parameters within the optimal limits.

The walls of the classroom model are divided into a number of bands along their height. As described initially, the lower 1.0 m of the wall is found to have a minimal effect on altering the acoustical features of the classroom and hence is maintained constant. The remaining 2.5 m of the wall height is divided into five equal bands of 0.5 m height. The best ceiling configuration obtained from the previous section that is of Case 6 is kept constant and the absorption of wall bands is increased to verify its effect on the acoustical indicators.

Results from simulations show better values of acoustical parameters as percentage absorption is increased on the upper bands of the walls than the middle portion of the walls suggesting the usage of limited beneficial reflections from the middle section of the wall area. At the same time reflections from the corner edges of the room ceiling and walls are found to be detrimental to the classroom acoustics as stressed upon in the literature. Initial simulations indicate the minimal effect of changing the absorption percentage of a single wall band of 0.5 m; instead multiple bands of the same wall bands with larger areas have a considerable bearing on the acoustical indicators.

Keeping the ceiling constant as in Case 6, the upper I m of the walls are assigned an absorption percentage of 40% with the middle 1.5 m portion of the walls assigned 30% absorption as shown in Figure 4.16 (Case 8). An evaluation of SI parameters shows the RT_{30} range well within the optimal range of 0.4 to 0.6 sec. A 'GOOD' STI rating is found in all the locations while a wider C_{50} range is noticed with the mean value of 5 dB. However, simulation results are representative of an unoccupied classroom due to the fact that all the data described in the references and measurements are evaluated classrooms in an unoccupied state. The scenario of the SI parametric results would change once the same model is simulated for occupied conditions and would result in the shifting of the RT_{30} range to a much lower value avoiding utilization of RT benefits.

Results of 9 receivers placed in the classroom of Case 8 reveal a low RT_{30} at locations near the back wall and a higher RT_{30} around the sidewalls. To overcome this, the back wall absorption percentage is reduced with all the five bands of the variant wall portion assigned absorption of 40% and then in the next simulation 50% as shown in Figure 4.16 (Case 9). The RT_{30} range increases with certain locations exceeding the optimum limits and the mean RT_{30} value also shifts to a higher value. A reduction of the C_{50} range is noticed. However no variation in STI values is seen. The results of Case 9 at nine receiver locations reveal low RT_{30} values at the locations nearer to the sidewalls while better values at the central portion of the classroom are indicative of improvements in the elimination of unwanted sound reflections from the edges and corners of the room.

In Case 10, the absorption percentage of the middle 1.5 m of the sidewalls is reduced to 20% and the upper 1.0 m band is assigned a 40% absorption level to overcome the shortcomings of the earlier case as shown in Figure 4.16 (Case 10). The RT_{30} value range increases with almost half of the range exceeding the optimum range and the mean shifts to a higher value.

However a narrower RT_{30} range is noticed than in the earlier case, which implies consistency in the acoustical indicators throughout the classroom. Similarly a reduced STI range is noticed with no change in the mean STI value along with a shift in the C_{50} average to a lower value. Locations near the back wall and some points at the center of the room are found to have a high RT_{30}, which are the cause of peak values within the range.

To limit the wider RT_{30} range found in Case 10, the upper 1.0 m of the back wall is provided with an absorption level of 50%. Improvements in the SI indicators are noted and are further enhanced by increasing the area of 50% absorption of the upper section of the back wall to 1.5 m as shown in Figure 4.16 (Case 11). A major reduction of RT_{30} range and values is found with a minor increase in the C_{50} range accompanied with a slight improvement in the STI values. Further reduction of the sound absorption of the sidewalls widens the RT_{30} range with no effect on STI. Therefore the possibility of altering the ceiling once again is looked at to further reduce the RT_{30} range.

The absorption percentage of the peripheral ring on the ceiling is reduced to 40% and better results are noticed associated with the narrowing of RT_{30}, C_{50} as well as STI ranges. To improve the RT_{30} values of some locations in the rear portion of the classroom, the back wall upper layer absorption is reduced to 40% as shown in Figure 4.16 (Case 12). A reduction in RT_{30} and C_{50} range is noticed. The peak value of RT_{30} is the same as Case 11 while the lower value shifts to a higher value. A shift in the RT_{30} average value is also noticed, but the whole range is expected to be within the optimal conditions of RT once the classroom is occupied. A minor reduction and shortening of the STI range is noticed within the 'GOOD' rating, while the best C_{50} values among all the simulations are observed.

More alterations in the wall and ceiling absorption material placement and absorption properties disturb the balance in the acoustical conditions in the modeled classroom. An increase in the absorption quantum in the same ratio as Case 12 reduces the RT_{30} values at most of the receiver locations but hampers the acoustical uniformity in the classroom resulting in wider RT_{30} and C_{50} ranges and at the same time does not improve the STI rating. Therefore Case 12 layout and absorption percentage is the best overall configuration for a typical smart classroom modeled in this study. The same configurations will enhance acoustical conditions in any classroom. However, depending upon the geometry and required listening conditions, minor modifications in terms of the absorption percentage in the Case 12 ratio of surface area and placement would be required.

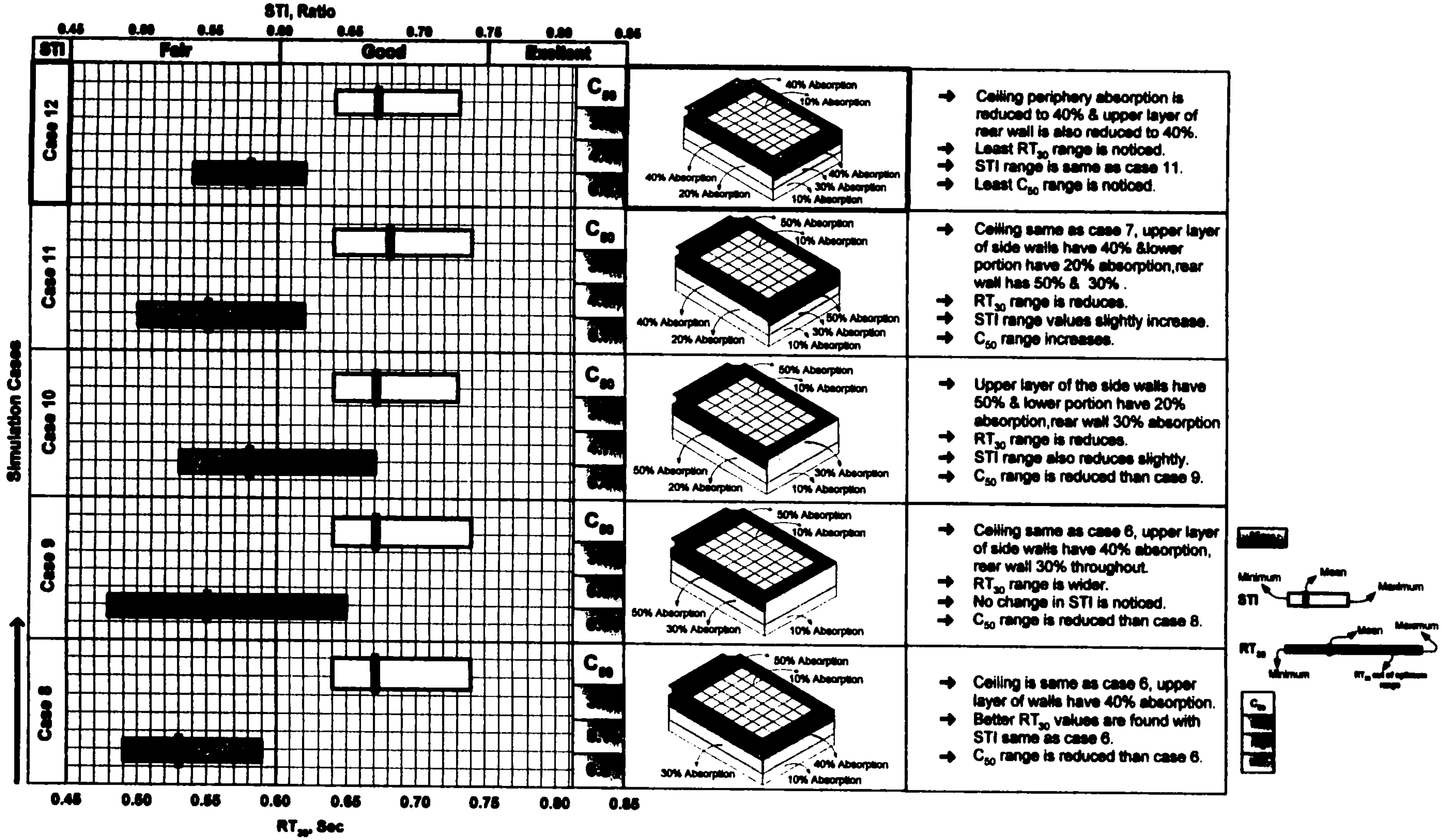


Figure 4.15. ***Investigation of best overall placement of acoustical absorption material in a typical smart classroom: Ceiling & wall investigation***

4.7 STEP 4: Comparing Sound-Absorbing Material Placement Alternatives

The ASA Classroom Acoustics resource for creating a learning environment with desirable listening conditions [1] describes three alternatives for improving acoustical conditions in classrooms. The configurations of sound-absorbing material of these three alternatives are utilized in the development of a smart classroom model and simulated to verify the effect on acoustical indicators. Results of the final layouts obtained from the three simulation steps described earlier in this Chapter are compared with these alternatives to study the improvements in the SI parameters. Although the layouts of both the schemes compared vary in terms of the sound absorption quantum and placement, the general concept and objectives are same.

The three layouts described in the ASA review on classroom acoustics as shown in Figure 4.17 depict a typical classroom with reflective surfaces in layout 'A'. Sound-absorbing material is placed on the ceiling in layout 'B' and layout 'C' shows a variation in the treatment of floor, three walls as well as the ceiling. A similar configuration of sound-absorbing material is assigned to the smart classroom model developed for this study. The allocated absorption percentage quantum is in conjunction with the sound-absorbing material properties found to yield good results in simulations highlighted in earlier sections.

Figure 4.18 depicts these three conditions with reflective surfaces in Condition 'A', 50% absorption on the ceiling of Condition 'B' and a 'U' shaped ring of absorption material on the ceiling periphery of Condition 'C' with 50% absorption, reflective ceiling on the center and over the instructor area along with 30% absorption on the three walls.

The results of Condition 'A' show a very high RT_{30} range calculated at the 9 receivers located throughout the room. The whole RT_{30} range is much higher than the recommended RT_{30} range. The C_{50} value range is narrow but with low values while the whole STI range lies in the 'FAIR' category. The grid response calculated at 1.2 m^2 grid shows a high SPL and low STI values for all receiver locations as seen in Figure 4.18 (Condition A).

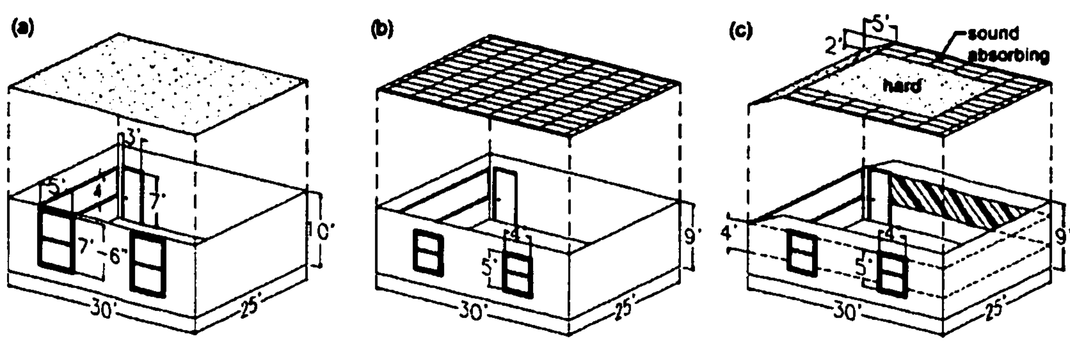


FIGURE 10. Classroom Layouts Classroom (a) is a typical undesirable room with no sound absorbing material and no useful reflection patterns. Classroom (b) is better with an acoustical lay-in, sound absorbing ceiling and thin carpeting. Classroom (c) is a desirable room with sound absorbing wall treatment on three walls, thin carpet, a sloped ceiling reflector at the front, and a ceiling with reflecting surfaces in the center and sound absorbing surfaces around the perimeter.

Figure 4.16. The three layouts of sound-absorbing material placement described in the ASA Classroom Acoustics resource for creating a learning environment with desirable listening conditions. (Adapted from [1 page 7])

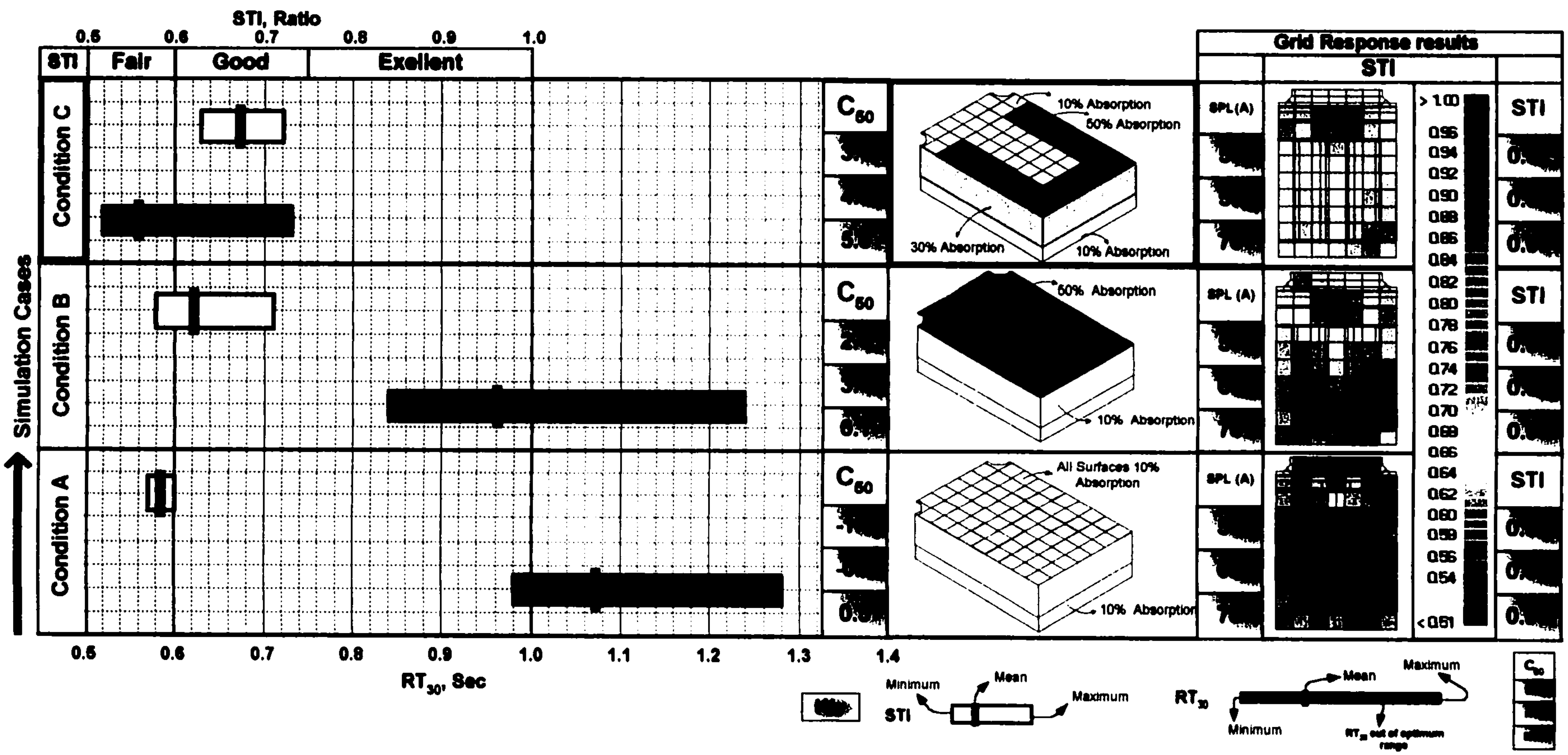


Figure 4.17. Results of the three alternative layouts recommended by ASA review on classroom acoustics [1], based on 9 receiver points and 1.2 m^2 grid response.

Condition 'B' results reveal a shift of RT_{30} range and mean values to a lower value. However a wider value range is noticed. The C_{50} range increases with improved values along with STI values with most of the STI range within the 'GOOD' rating accompanied with an increase in the range length. Minimal effect is noticed on SPL(A) from the grid response results while an improvement in STI values is seen as shown in Figure 4.18 (Condition B).

Condition 'C' depicts the best results with shorter RT_{30}, C_{50} and STI ranges. The RT_{30} average value is within the optimum range while most of the range length exceeds the classroom optimum RT_{30} limit of 0.6 sec. The whole of the STI range is within the 'GOOD' rating with a mean of 0.67. SPL(A) results calculated from the 1.2 m^2 grid response reveal a minor reduction of SPL(A) at certain points while a major improvement in STI values is evident from Figure 4.18 (Condition C).

The simulation cases with best results described in simulation steps 1 to 3 are compared in Figure 4.19. These cases represent almost similar conceptual layouts as described earlier for ASA recommended alternatives in Figure 4.18, the only difference being the variation in sound-absorbing material quality. Case 1 shown in Figure 4.19 has the ceiling and all the three walls allocated a percentage absorption level of 30% except for the lower 1.0 m band. The result is a wider RT_{30} range and a 'GOOD' STI rating. In comparison to condition 'A' of Figure 4.18, much better RT_{30} values are noticed along with C_{50} and STI range values. The grid response results suggest a major improvement in the STI values throughout the classroom with the application of sound-absorbing materials. SPL(A) values as expected decrease when absorption material is assigned on the modeled classroom surfaces.

Comparing the results of condition 'B' of Figure 4.18 and Case 6 of Figure 4.19, a noticeable variation of acoustical parameters is observed. The RT_{30} in Condition 'B' exceeds the optimal RT_{30} range while in Case 6, most of the range is within the optimal range along with the average value. Better C_{50} and STI ranges are also noticed with similar results observed from the 1.2 m^2 grid response.

The best sound-absorbing material configuration formulated in Step 3 simulations, that is Case 12 as shown in Figure 4.19, when compared with Condition 'C' of Figure 4.18 depicts an overall enhancement of SI indicators in the former layout over the later configuration. A shorter RT_{30} range with better values is found in Case 12 than in condition 'C'. Similar results are observed from the comparison of C_{50} and STI value ranges. The grid response results also show improvements in the STI values throughout the classroom in Case 12 while similar SPL(A) values are noticed in both layouts. The whole exercise described in this section clearly suggests that classroom sound-absorbing material placement and percentage absorption characteristics achieved from the simulations in Step 1 through Step 3 have an edge over the recommendations provided by the ASA review on classroom acoustics. Utilizing Case 12 configuration of sound-absorbing materials, better sound quality can be achieved enhancing SI within the classroom.

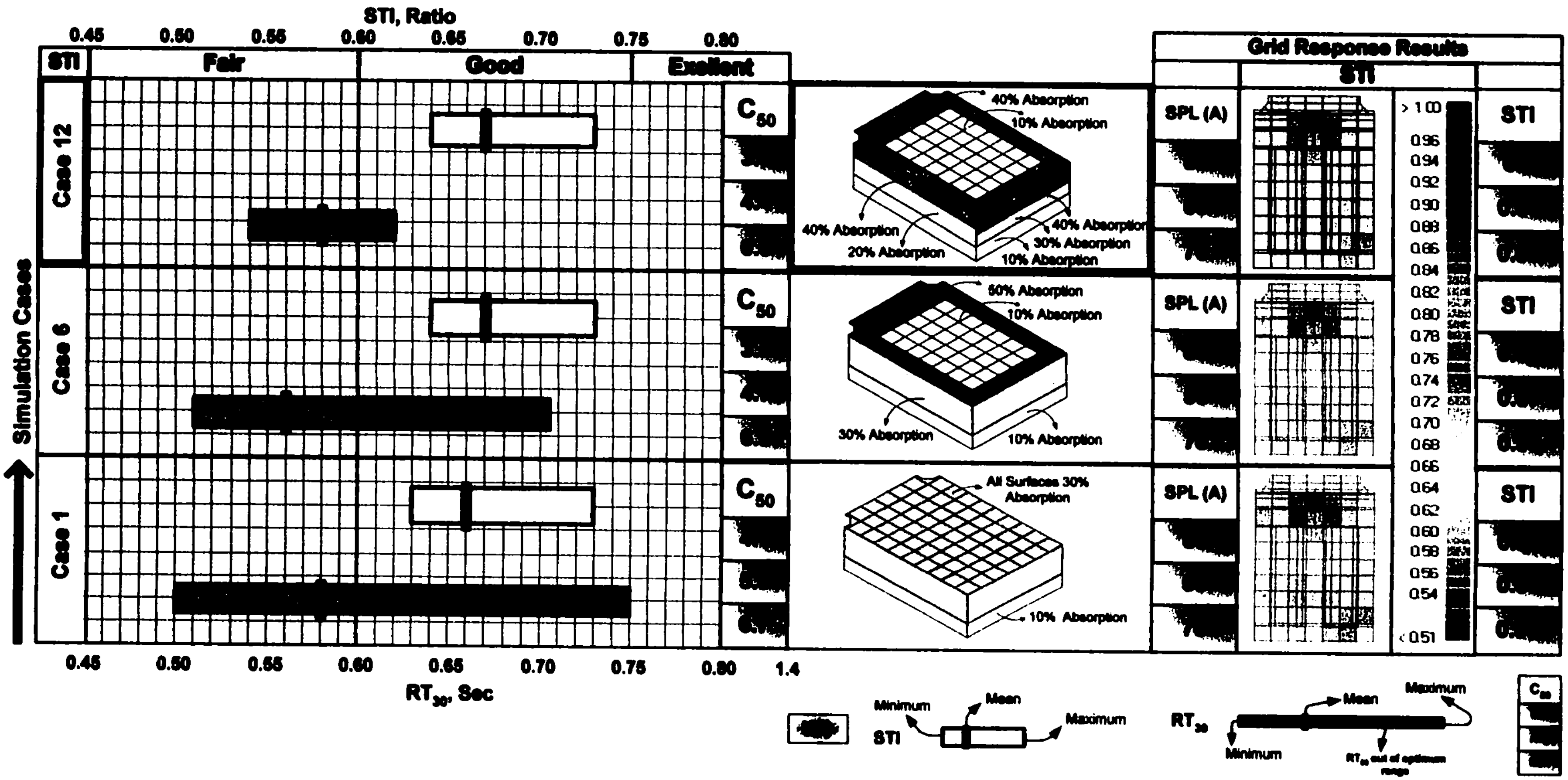


Figure 4.18. *Results of the three best cases obtained from simulation steps 1 through 3, based on 9 receiver points and 1.2 m^2 grid response.*

4.8 STEP 5: The Effect of Background Noise (BN) on Speech Intelligibility (SI)

Background noise (BN) measurements in existing university classrooms as described in Section 3.4.2 have a detrimental effect on Speech Intelligibility (SI). Noise generated by instructional equipment adds up to the existing BN of the classroom as described in Section 3.6. The measurements of existing classrooms meant for formal lecture delivery as well as classrooms equipped with instructional equipment such as data projectors, PC's, audio-visual equipment and networking equipment, highlight the fact that most of the classrooms have a BN ranging from NC-25 to NC-35 rating. This range is also specified in literature to be the BN range in classrooms [59]. However, the latest ANSI standard on classroom acoustics [54] specifies a BN limit of 35 dB-A for classrooms which falls under the NC-25 rating.

In this Section, the best overall configuration of sound-absorbing material placement and quantum selected from Step 3 simulations (Section 4.6) is again modeled changing the BN. Case 12 is simulated with different BN characteristics ranging from NC-20 to NC-40 for verification of effects on SI under least possible classroom ambient noise as well as the maximum allowable BN beyond which the functionality is drastically affected. As found from the measurements of classrooms equipped with instructional equipment (Section 3.6), the BN shifts to an NC rating one step higher once the equipment is 'ON'. This means that if the classroom has an existing ambient noise corresponding to the NC-35 rating, with equipment 'ON', the overall BN would shift to NC-40 with a further detrimental effect on SI.

However, SI in a classroom is also a function of the SPL and frequency characteristics of an instructor's speech. This issue is also verified by simulating the Case 12 configuration under the commonly found classroom BN ranging from NC-25 to NC-35 using a 'Talk Normal' sound source. The 'Talk Normal' sound source is representative of a speaker with a mild and dry tone. The acoustical indicators are compared to substantiate the effects of various BN ratings on SI in the modeled smart classroom.

Figure 4.20 depicts the parametric comparison of SI indicators at various NC ratings. With a BN of NC-40 rating, STI falls to the 'FAIR' category with a wide value range throughout the classroom. The scenario improves under the BN of NC-35 rating; the range decreases with most of its length within the 'GOOD' rating. As the BN is further reduced to NC-30, a shorter STI range is noticed under 'GOOD' rating. Improvements in STI value ranges are found as the BN is reduced to NC-25 and NC-20 accompanied with the shortening of the value range. Figure 4.20 clearly highlights the importance of BN containment for enhanced SI.

The evaluation of simulation results with a 'Talk Normal' sound source reveal lower STI values under all the BN situations other than that of a 'Talk Raised' sound source. At NC-35 BN, the range is wider falling under the 'FAIR' category while with NC-30, most of the STI range lies in 'GOOD' rating but the values along with mean are much lower than the STI rating found using a 'Talk Raised' sound source. Similar results are noticed at NC-25 rating highlighting the fact that in order to make their conversation comprehendible, instructors have to raise their voice under noisy conditions depending upon the instructor's speech level, which often causes vocal fatigue and strain. In smart classrooms, the instructors are exposed to tougher conditions as instructional equipment increases the existing BN of the classroom.

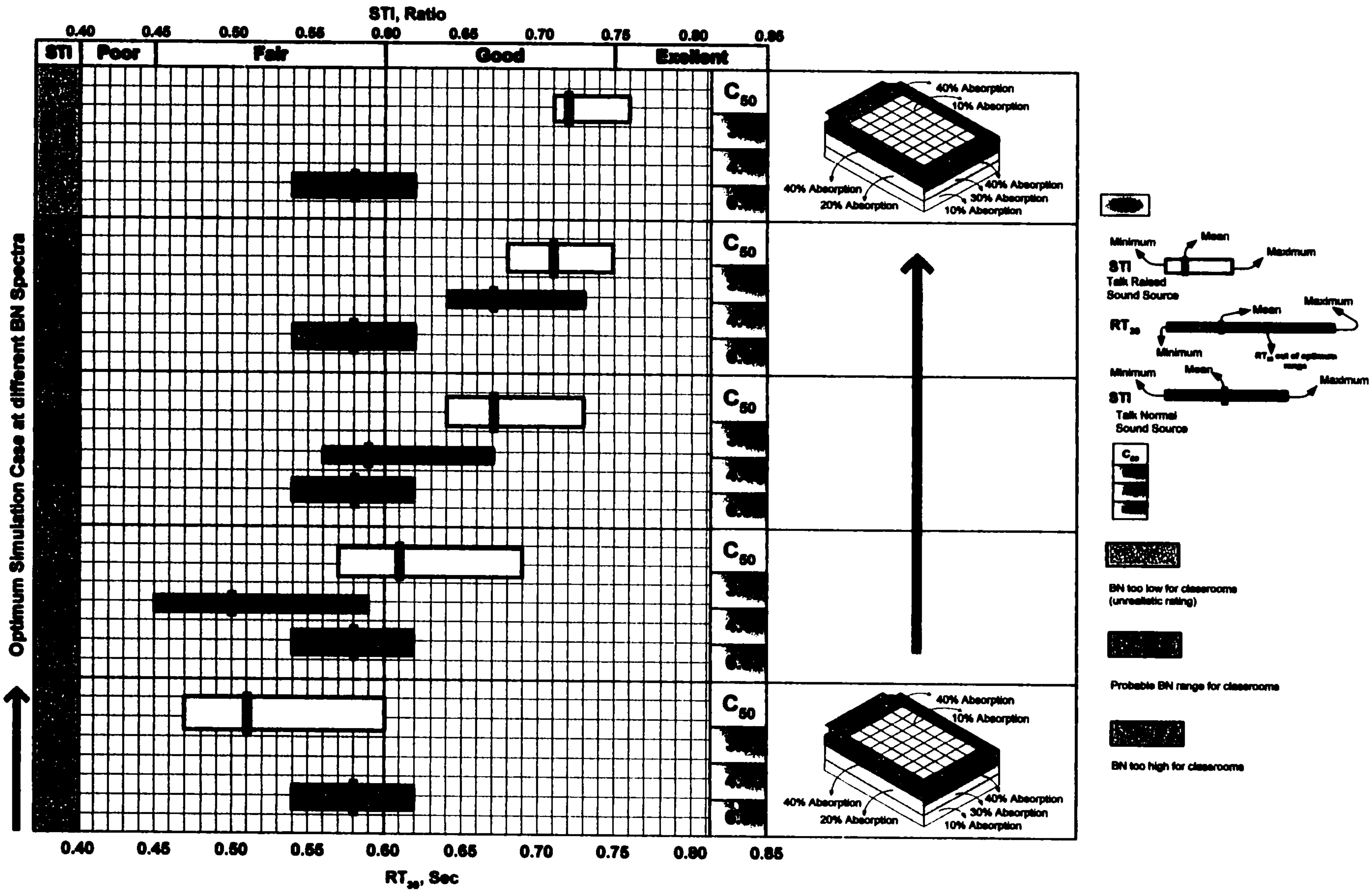


Figure 4.19. Results of Case 12 SI parameters simulated at different background noise ratings.

CHAPTER 5

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary

Acoustical quality is a major concern in classrooms; it is essential for classrooms to have good acoustical conditions for un-obstructed and efficient comprehension of the instructor's speech. Studies suggest that inappropriate acoustical conditions in classrooms result in students missing 25% of the instructor's spoken words [1] with the situation further deteriorating when non-native listeners or students with hearing difficulties are present in the classroom. Good classroom acoustics is important for teachers as well and can be a cause of vocal fatigue and strain. The teacher's speech level and frequency content has an impact on the listening conditions in a classroom. However, tailoring human speech for teaching purposes is highly cumbersome and not a practical solution. Although nothing much can be done about the teacher's voice, the behavior of sound in a classroom enclosure can be looked at and studied to fit the requirements. The integration of a sound reinforcement system is an alternate solution recommended by some professionals, which is a cause of increased damage to listening conditions in an already acoustically poor classroom and should be avoided. The high ambient noise level in classrooms is one of the main features that degrade the acoustical ambience of a classroom enclosure. Surveys prove that most of the present classrooms in educational establishments have high Background Noise (BN) generated by Heating, Ventilation and Air-Conditioning (HVAC) systems, lighting fixtures and externally transmitted noise [44, 46, 47]. Although strict recommendations for BN generated by equipment related to classroom facilities have been laid, most of the time these recommendations are not adhered to.

The realization of the benefits of good acoustical conditions and Speech Intelligibility (SI) in classrooms in addition to financial gains associated with improved acoustics in classrooms has led researchers and education institutions in the western world to standardize the main physical elements of the classroom [53]. These concerns have led to the development of the American National Standards Institute (ANSI) standard on classroom acoustics in the United States of America [54], while institutions in the rest of the world are still skeptical about the area mainly due to the high initial cost involved.

Advancement in technology has led to the development of a new generation of classrooms referred to as 'smart classrooms', with enhanced audio-visual facilities and interactive learning. Such specialized classrooms are a part of a modern educational system associated with the introduction of a variety of instructional equipment into the classroom. The addition of instructional equipment in smart classrooms further complicates the issue of classroom acoustics as equipment-generated noise increases the already existing BN within the classroom. Instructional equipment is loaded with power supply units, fans and transformers, which generate noise. Multiples of such equipment add up and increase the noise within the enclosure, degrading the SI in such classrooms. Earlier research and the latest ANSI standard on classroom acoustics tend to overlook these issues [54]. Some studies even assume the instructional equipment generated noise to be negligible [48]. Therefore, this study is an attempt to highlight the issue of instructional equipment generated noise within the smart classrooms.

The behavior of sound emitted by a sound source and the noise levels produced within a classroom are largely determined by the sound absorbing properties of the surfaces in the room [60]. Thus, the aim of this research is to understand the physical aspects of classrooms that affect the acoustics in these enclosures meant for learning and compare the same with that of the modern classrooms (i.e. smart classrooms which are equipped with additional instructional equipment). The effect of the room physical characteristics on SI is studied and alternatives formulated to achieve an overall best alternative for enhanced SI. Investigation is carried out to organize the room finishing materials in a systematic manner to optimize classroom acoustics and evaluate the impact of various BN levels on the ultimate solution. This evaluation provides an overview of the best overall smart classroom acoustical performance under various BN levels considering the classroom noise level recommendations mentioned in literature and standards.

To achieve the previously stated goal, a thorough study of the acoustical indicators that objectively define the SI in a classroom is carried out. The contemporary descriptors of SI that guide evaluation of acoustical conditions in an enclosure are studied in detail and later used to evaluate the sound quality in classrooms. This study is nevertheless limited to the parametric evaluation of SI predictors to identify an ideal smart classroom material configuration and the best material assignment for enhanced SI. The scope extends to the modeling of a typical smart classroom with physical assembly reflecting the modern classroom characteristics. The impact of instructional equipment on the ambient noise and SI is investigated for the best sound-absorbing material configuration. Evaluation of optimum classroom geometry, its layout and the effect of noise generated by the equipment as isolated point sources are beyond the scope of this research.

In order to enhance the understanding of the influencing acoustical parameters and to assess the impact of classroom physical elements in addition to noise conditions, measurements are conducted in existing un-occupied university classrooms using the Maximum Length Sequence System Analyzer (MLSSA), a computer based sound measurement and analysis package. Six university classrooms in KFUPM campus used for conventional lecture delivery as well as computer aided interactive learning classrooms are selected on the basis of being representative of most of the classrooms at

KFUPM. The BN in these classrooms is also measured to assess the range of noise students are usually exposed to in these learning spaces. In addition to this, the impact of instructional equipment on the BN of a classroom is also evaluated by measuring the BN in conditions with the equipment both 'ON' and 'OFF'. The variation trends of the measured acoustical parameters in these classrooms are developed from the average values of the measured data to assess their relationship.

The results of the measurements reveal the presence of a high Reverberation Time (RT_{30}) in the majority of the classrooms with the Clarity (C_{50}) values beyond the recommended range especially in the mid-frequency range where the speech energy is dominant. Mainly due to the presence of highly reflective surfaces, some of these classrooms are acoustically unfit for their function. The range of the measured indicator values also varies throughout the classroom which suggests the uneven distribution of acoustical conditions. The SI ratings suggest that most of the classrooms fall within the range of 'POOR' and 'GOOD' rating accompanied with a large spatial variation of SI values. The majority of the existing classrooms are found to have high BN levels exceeding the BN limit recommended by the ANSI standard on classroom acoustics. The noise generated by the instructional equipment is found to increase the already existing BN by at least five NC curve (Noise Criteria) rating accompanied with a shift in the frequency of influence towards high frequency dominance.

Based on the characteristic analysis of existing smart classrooms, a model of a typical smart classroom is developed housing 24 to 28 workstations using CAD software. To investigate the impact of sound-absorbing material type and placement on various portions of the room surfaces, the walls are divided into six bands and the ceiling is fragmented into a number of tiles. The model is simulated using ODEON 5.0 room acoustics software. Model surfaces are exemplified into two categories that is, surfaces with consistent sound-absorbing material characteristics throughout the simulations and those with varying sound-absorbing characteristics. Two sound sources and nine sound receivers are allocated throughout the model to evaluate the acoustical conditions.

The simulations are carried out in five steps. In each step, acoustical indicators like RT_{30}, C_{50} and STI are calculated and compared. The first step reveals the base case model which is further used for detailed simulations. In the second step, best ceiling layout of sound-absorbing material is achieved keeping the walls at constant absorption characteristics as obtained from earlier simulation step. It is found that providing sound-absorbing material having 40 to 60 percent absorption potential in the periphery of the room ceiling with sound reflective material on the remaining central portion of the ceiling yields better results. In the next step, an overall best sound-absorbing material configuration of walls and ceiling is formulated. The simulation results reveal acoustical improvement as the central portion of the walls are assigned a sound absorption percentage of 20 to 30% and the upper portion of the walls forming the intersection with the ceiling allocated a sound absorption percentage of 40 to 60% similar to that of the ceiling peripheral tiles. To confirm the validation of the results, alternatives recommended by ASA for sound-absorbing material placement and characteristics in classrooms are compared with the similar layouts achieved in earlier described simulation steps of this study. All the cases formulated in this research show better results compared to the ASA alternatives, thus validating the outcome of the investigation carried out in this study.

To examine the effect of Background Noise (BN) of various levels on SI, the overall best configuration of sound-absorbing material placement is simulated under different NC ratings. The most likely BN ratings assessed from the measurements of the existing classrooms are selected as noise inputs. The range of ambient noise selected is also representative of the increase in the BN due to instructional equipment noise, which increases the NC rating by 5 to10 NC. The results show an improvement in SI as the BN decreases from NC-40 to NC-20. The common NC ratings found in classrooms that is NC-25 to NC-35, is also simulated utilizing a 'Talk Normal' sound source which mimics the speech spectrum of an instructor with low or mild speech levels. This allows examination of SI conditions under both limits with speakers speaking in low tone as well with raised voice. The results depict a similar pattern of SI indicator as in case of a 'Talk Raised' sound source with improvements noticed as the BN decreases. However, with normal speech the situation worsens under high noise conditions, which forces an instructor to raise his voice causing vocal strain.

The results support the maximum permissible BN level of 35-dB(A) (NC-25) recommended by the ANSI standard [54] on classroom acoustics as essential for smart classrooms. Although the standard overlooks the noise generated by the instructional equipment, the same rating yields good listening conditions in smart classrooms as well. There is no doubt that a reduced BN level of less than NC-25 will be much better for classrooms with a large amount of permanent instructional equipment, the presence of which will increase the BN within the smart classroom by at least 5-NC rating. However due to practical reasons and high initial cost involvements in maintaining a BN of NC-20 in classrooms, strict adherence to the ANSI specified level of ambient noise is recommended for smart classrooms which will result in an overall BN of NC-30 in such rooms with all the equipment 'ON'. An increase in the ambient noise beyond this limit will be detrimental to SI in these specialized classrooms.

5.2 Conclusions

Good acoustical environment is essential in learning spaces where as improper listening conditions in classrooms degrade Speech Intelligibility (SI) affecting student comprehension capabilities. In this study a smart classroom model has been developed which is simulated to achieve the best overall configuration of sound-absorbing material placement and characteristics. To validate the outcome of the formulated best overall sound-absorbing material layout, results are compared with the recommendations for the same described by Acoustical Society of America (ASA). Ultimately, an acceptable Background Noise (BN) level for a typical smart classroom is identified that would result in better SI.

With the associated disadvantages in a poor classroom acoustical environment, serious emphasis should be given to improving the listening conditions in classrooms. Guidelines should be set at institutional levels for acoustical detailing at the design stage as well as for retrofitting of existing classrooms. The conversion and re-design of conventional classrooms to smart classrooms necessitates acoustical design. As long term educational and financial benefits are also associated with such improvements, awareness and appreciation of better classroom acoustics become the first and foremost step, which is one of the main purposes of this study.

The main cause of unacceptable acoustical conditions in rooms is the presence of inappropriate surface finishing. Reflective surfaces generate multiple reflections, which render a room highly reverberant blurring the speech signals. Similarly the presence of high BN generated by HVAC systems, lighting fixtures and instructional equipment reduces the signal to noise ratio degrading SI within a classroom. Therefore, it is essential to restrict the BN of a classroom within the recommended noise levels.

To overcome these listening problems, two basic remedial measures in the case of retrofitting projects or essential design guidelines in the case of new classroom construction as resulted from the developed model are stated below:

1. Treatment of classroom surfaces with optimal placement and magnitude of sound-absorbing material.

2. Restriction of the overall BN in a classroom to recommended noise levels.

The treatment of classroom floor, ceiling and wall surfaces with the best overall configuration of sound-absorbing material reduces the excessive reverberation time to the recommended range for Speech Intelligibility (SI). Placement of absorption material of different absorption characteristics in an efficient manner improves the listening conditions within a classroom and at the same time restricts the amplification of internally generated noise.

Utilization of such absorption configurations is essential for smart classrooms and other similar learning spaces.

The best overall sound-absorbing material characteristics and placement (Figure 5.1) evolved from this study can be used to enhance acoustics in conventional as well as smart classrooms. The features of the recommended layout are described below in Table 5.1.

The utilization of sound-absorbing material of different absorption potentials at mid-frequency ranges used in Table 5.1 in the described configuration results in good acoustical balance throughout the classroom and hence better SI. A list of possible sound-absorbing materials that can be used in classrooms with their sound absorption spectral characteristics and Noise Reduction Coefficient (NRC) is given in Appendix B. The list can be useful in the selection of suitable sound-absorbing material to satisfy the requirements and to achieve the objective of SI enhancement in classrooms. The next essential step for developing a better listening environment in classrooms is to contain the BN within the recommended level as specified by the ANSI standard on classroom acoustics of 35 dB(A), which falls within the NC-25 rating. In smart classrooms, the internally generated noise increases the ambient noise to at least 5-NC rating higher. Therefore it is essential to restrict the BN of such learning spaces to the recommended NC-25 rating although it would be better to lower the BN rating involving high initial cost and less practicality. In addition, measures described in Appendix C would be beneficial in limiting the BN of a conventional as well as a smart classroom to the acceptable levels resulting in good acoustical conditions and improved SI.

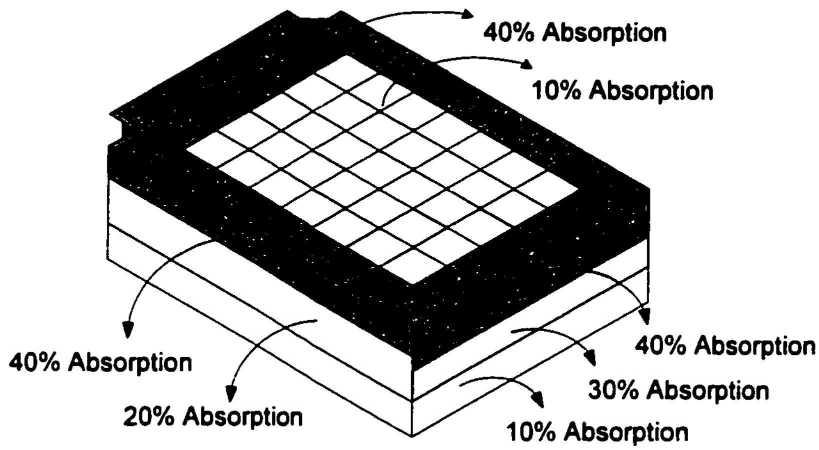


Figure 5.1. The developed smart classroom model showing the best overall sound absorbing material placement and absorption characteristics

Table 5.1. The sound-absorbing material configuration that results in good acoustical conditions.

Room Surface	Material type to be used	Approximate area & configuration	Percentage absorption (%)[1]
Floor	Carpet	Whole floor	Light weight carpet or higher thickness (40%)
Ceiling	Sound absorptive ceiling panels	40% of the ceiling area around the periphery	40% to 60%
		60% of the central area	Reflective material (10%)
Wall	Gypsum or other smooth plaster	Lower 25% of the wall area	Smooth finishing (10% to 20%)
	Sound absorptive panel or plaster	Middle 50% area of the wall	20% to 30%
	Sound absorptive panel	Upper 25% of the wall area	40% to 60%

[1] Mean at 500, 1000 and 2000 Hz frequency.

*Note: Appendix B can be used to specify surface finishes that satisfy the recommended percentage absorption.

5.3 Recommendations for Future Studies

This research provides an overview of the issues and concerns related to the optimization of the acoustical environment within conventional as well as new generation of smart classrooms. The best overall configuration of smart classroom finishes is formulated along with the required BN level for enhanced SI. However, it is essential to practically verify the impact of the evolved sound-absorbing material layout. This can be achieved by the implementation of proposed smart classroom configuration as described in this study in one of the existing classrooms. The objective SI indicators can then be measured and compared with other classrooms to verify the effectiveness of the developed model.

Also, the study is limited to the most common and typical rectangular geometry of a classroom, which is a variable factor. In the near future, more complicated geometry will take the typical classroom to forms such as fan shaped classrooms with domical projection surfaces for immersed visual display. Hence acoustical conditions in different classroom geometry need to be studied in future. Another aspect that needs attention is to standardize the noise generated by isolated instructional equipment so that the effect of these noise sources can be assessed as point sources and their effect quantified.

This would require more details about the noise spectrum and sound power level of the instructional equipment.

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APPENDIX A

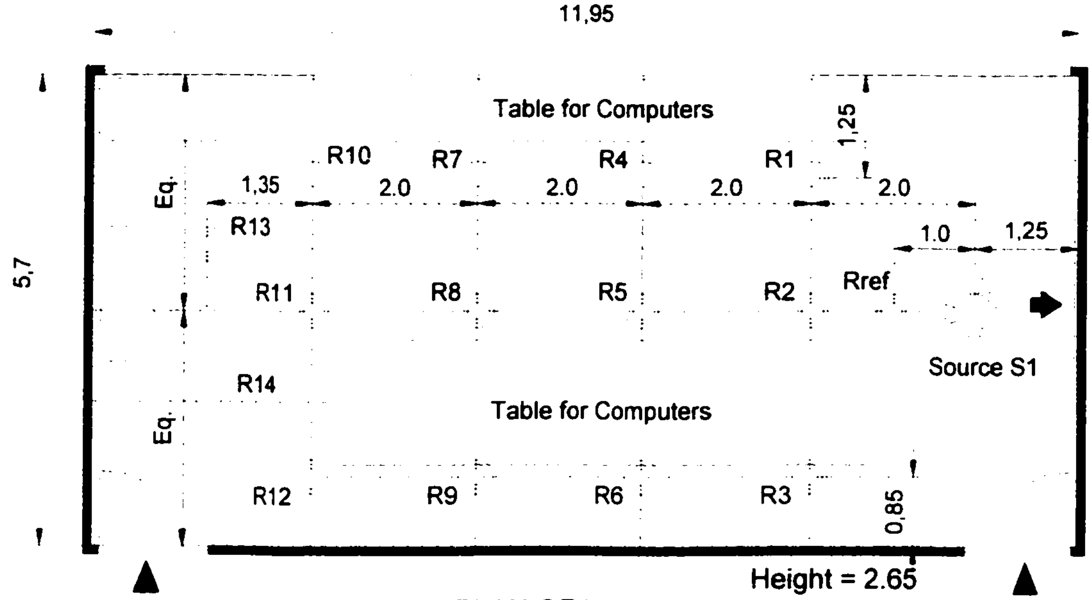


Figure A (1a). Documentation of sample computer lab 14-105. Test sound source and measurement locations are also shown.

LEGEND

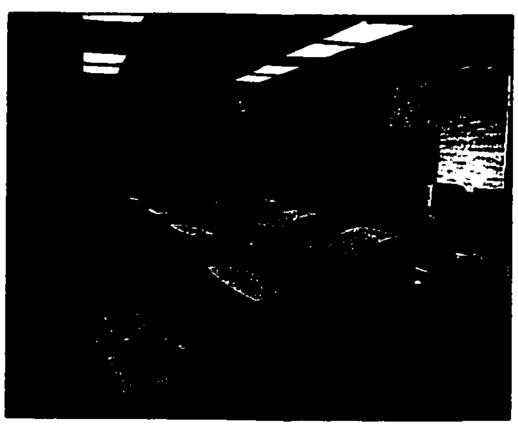
Sound Source

Sound Receiver

General Information:-

Classroom reference number:	**14-105**
Dimensions (L x W x H):	**12.0 x 5.8 x 2.65 (m)**
Room aspect ratio:	**2.0**
Volume (m^3):	**184**
Capacity (persons):	**30**

Usage: Computer Laboratory



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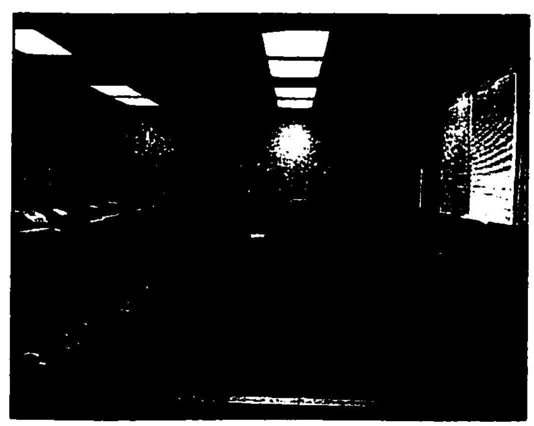


(c)

Figure A (1b & 1c). Interior views of computer lab 14-105.

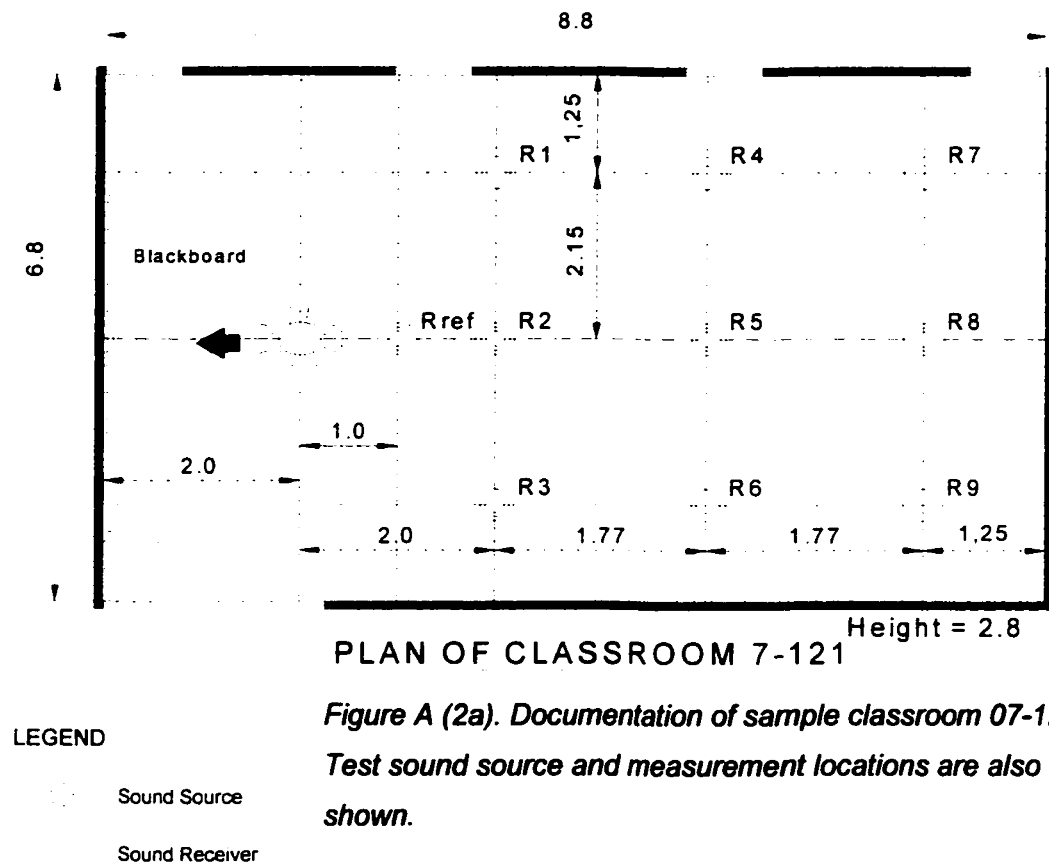


Figure A (2a). Documentation of sample classroom 07-121. Test sound source and measurement locations are also shown.

General Information:-

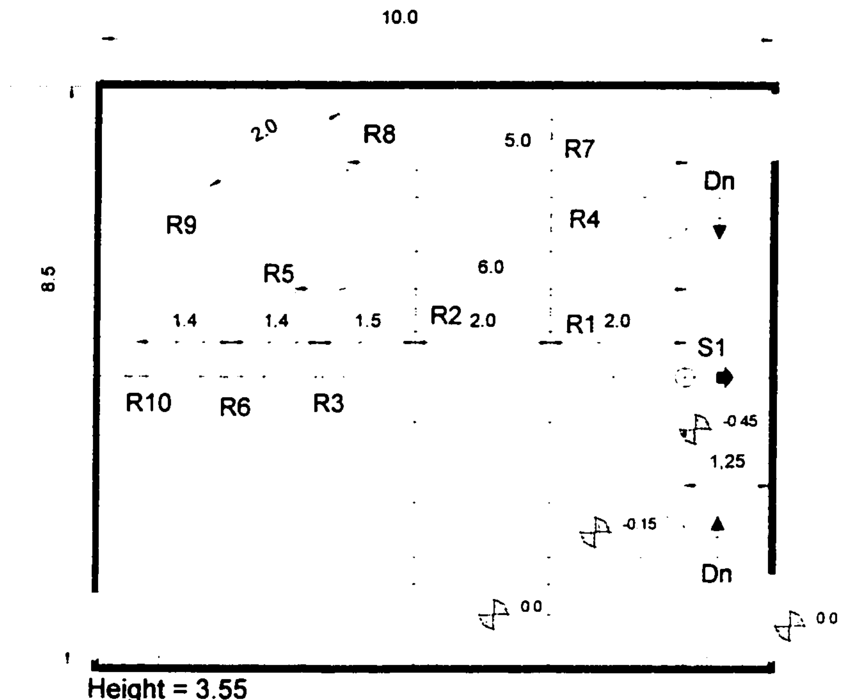
Classroom reference number:	07-121
Dimensions (L x W x H):	8.8 x 6.8 x 2.8 (m)
Room aspect ratio:	1.3
Volume (m^3):	165
Capacity (persons):	35

Usage: Regular Classroom

(b)

(c)

Figure A (2b & 2c). Interior views of classroom 07-121.



PLAN 24-115

LEGEND

Sound Source

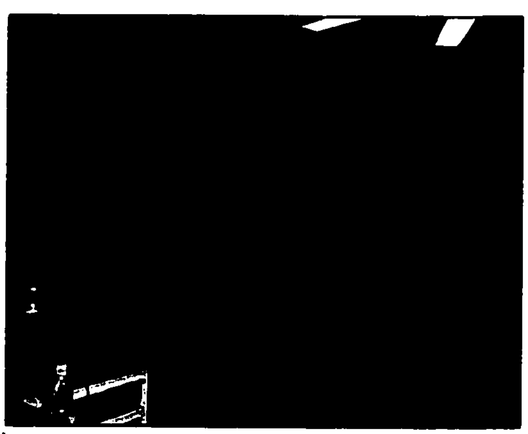
Sound Receiver

Figure A (3a). Documentation of sample presentation classroom 24-115. Test sound source and measurement locations are also shown.

General Information:-

Classroom reference number:	24-115
Dimensions (L x W x H):	10.0 x 8.5 x 3.5 (m)
Room aspect ratio:	1.2
Volume (m^3):	300
Capacity (persons):	35

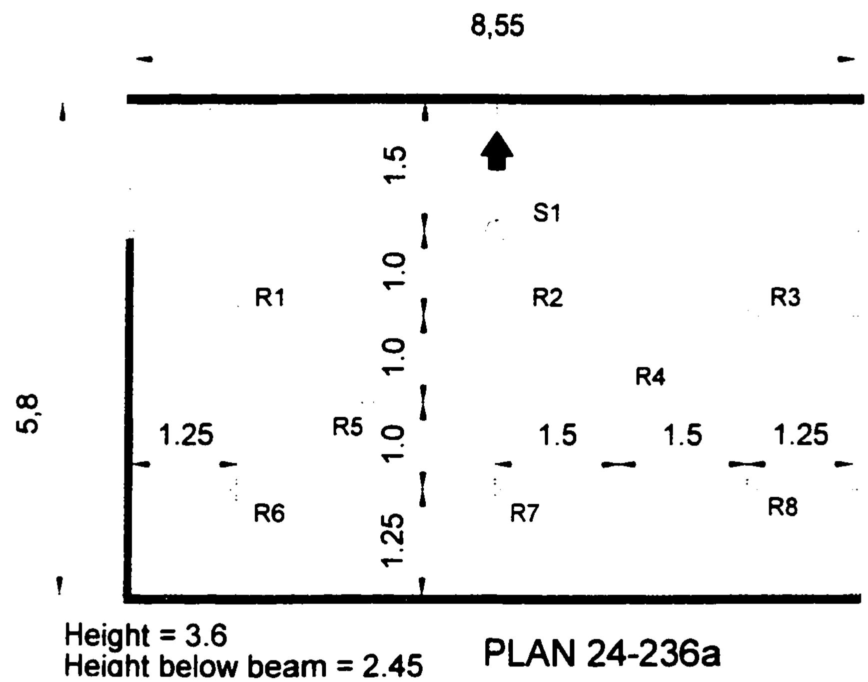
Usage: Presentation Classroom



(b)

(c)

Figure A (3b & 3c). Interior views of presentation room 24-115.



LEGEND

Sound Source

Sound Receiver

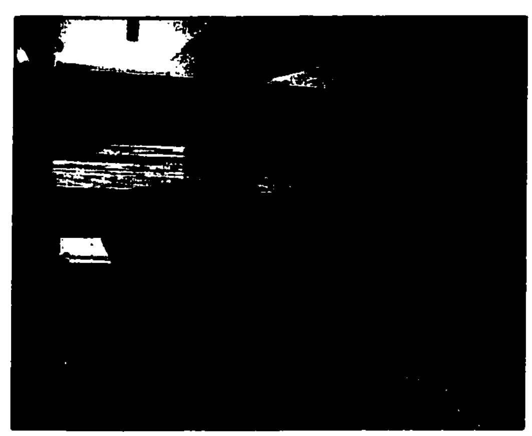
Figure A (4a). Documentation of sample presentation classroom 24-236a. Test sound source and measurement locations are also shown.

General Information:-

Classroom reference number:	24-236a
Dimensions (L x W x H):	8.55 x 5.8 x 3.5 (m)
Room aspect ratio:	1.5
Volume (m^3):	175
Capacity (persons):	30

Usage: Presentation Classroom

(b)



(c)

Figure A (4b & 4c). Interior views of presentation room 24-236a.

APPENDIX B

List of sound absorption materials that can be used for acoustical treatment of ceilings and walls of classrooms with their spectral absorption characteristics are described below (obtained from the ODEON acoustical software database). The mid-frequency average at 500 to 2000 Hz along with the NRC rating value is also shown on the right side of the table.

Table B1. List of sound absorption materials.

Frequency Ref.# Odeon	63	125	250	500	1000	2000	4000	8000	Average 500-2000	NRC
505	Needle felt 5mm stuck to concrete (Ref. SBI/13)									
	0.01	0.01	0.02	0.05	0.15	0.3	0.4	0.4	0.17	0.13
506	6mm pile carpet bonded to closed-cell foam underlay (Ref. 18)									
	0.03	0.03	0.09	0.25	0.31	0.33	0.44	0.44	0.30	0.25
507	6mm pile carpet bonded to open-cell foam underlay (Ref. 18)									
	0.03	0.03	0.09	0.2	0.54	0.7	0.72	0.72	0.48	0.38
508	9mm tufted pile carpet on felt underlay (Ref. 18)									
	0.08	0.08	0.08	0.3	0.6	0.75	0.8	0.8	0.55	0.43
1005	3.5-4 mm boards (asbestos, plywood or hard fiberboard), 4.5-5 mm holes in square pattern with approx. 13% perforation, on frame construction:									
	0.08	0.08	0.2	0.55	0.65	0.5	0.4	0.4	0.57	0.48
1006	As above: 75 mm cavity with 25 mm mineral wool at front of cavity									
	0.2	0.2	0.4	0.65	0.6	0.5	0.4	0.4	0.58	0.54
1007	As above: 50 mm cavity with 50 mm mineral wool									
	0.15	0.15	0.6	0.8	0.6	0.5	0.4	0.4	0.63	0.63
1008	1008 As above: 0.5 m cavity with 100 mm mineral wool at front of cavity									
	0.7	0.7	0.8	0.75	0.6	0.5	0.4	0.4	0.62	0.66
1100	50 mm mineral wool (40 kg/m3), glued to wall, untreated surface									
	0.15	0.15	0.7	0.6	0.6	0.85	0.9	0.9	0.68	0.69
1101	50 mm mineral wool (40 kg/m3), glued to wall, surface sprayed with thin plastic solution (Ref. SBI/13)									
	0.15	0.15	0.7	0.6	0.6	0.75	0.75	0.75	0.65	0.66
1102	50 mm mineral wool (70 kg/m3) 300 mm in front of wall (Ref. SBI/13)									
	0.7	0.7	0.45	0.65	0.6	0.75	0.65	0.65	0.67	0.61
1103	50 mm wood-wool set in mortar (Ref. SBI/13)									
	0.08	0.08	0.17	0.35	0.45	0.65	0.65	0.65	0.48	0.41
1104	Acoustic plaster' (Ref. 13)									
	0.15	0.15	0.25	0.4	0.55	0.6	0.6	0.6	0.52	0.45
2014	Fiberglass boards and blankets, 2,54 cm glass wool, 24 to 48 kg/m^3									
	0.08	0.08	0.25	0.65	0.85	0.8	0.75	0.75	0.77	0.64
2015	Fiberglass boards and blankets, 5.1 cm glass wool, 24 to 48 kg/m^3									
	0.17	0.17	0.55	0.8	0.9	0.85	0.8	0.8	0.85	0.78
2016	Fiberglass boards and blankets, 2.54 cm glass wool, 2.54 cm airspace									
	0.15	0.15	0.55	0.8	0.9	0.85	0.8	0.8	0.85	0.78

2017	Fiberglass boards and blankets, 5.1 cm fiberglass, panels with plastic sheet wrapping and perforated metal facing		
	0.33 0.33 0.79 0.99 0.91 0.76 0.64 0.64	0.89	0.86
2026	Mineral spray-on materials, 1.27 cm mineral fiber		
	0.05 0.05 0.15 0.45 0.7 0.8 0.8 0.8	0.65	0.53
2027	Mineral spray-on materials, 1.9 cm mineral fiber Ref.		
	0.1 0.1 0.3 0.6 0.9 0.9 0.95 0.95	0.8	0.68
2028	Mineral spray-on materials, 2.5 cm mineral fiber Ref. Harris:		
	0.16 0.16 0.45 0.7 0.9 0.9 0.85 0.85	0.83	0.74
2029	Mineral spray-on materials, 1.27 cm mineral fiber on metal lath, 2.54 cm airspace		
	0.25 0.25 0.5 0.8 0.9 0.9 0.85 0.85	0.87	0.78
2033	Plywood paneling, 1 cm thick Ref. Harris:		
	0.28 0.28 0.22 0.17 0.09 0.1 0.11 0.11	0.12	0.15
2310	Walls, gypsum board, 2 layers total 32 mm		
	0.28 0.28 0.12 0.1 0.17 0.13 0.09 0.09	0.13	0.13
2319	Ceilings, 16 mm pressed mineralfiber board (fissured) 20 mm from ceiling		
	0.09 0.09 0.4 0.56 0.59 0.7 0.69 0.69	0.62	0.56
2320	Ceilings, 16 mm pressed mineral fiber board (fissured) 210 mm from ceiling		
	0.38 0.38 0.28 0.39 0.59 0.64 0.65 0.65	0.54	0.48
2321	Ceilings, 25 mm thick, against ceiling		
	0.05 0.05 0.21 0.59 0.83 0.87 0.91 0.91	0.76	0.63
2322	Ceilings, 50 mm thick, against ceiling		
	0.15 0.15 0.56 0.88 0.99 0.99 0.95 0.95	0.95	0.86
2323	Ceilings, 100 mm thick, against ceiling		
	0.58 0.58 0.69 0.96 0.97 0.99 0.91 0.91	0.97	0.90
2324	Ceilings, 25mm thick, 200 mm from ceiling		
	0.48 0.48 0.49 0.7 0.78 0.94 0.93 0.93	0.81	0.73
2325	Ceilings, 50 mm thick, 200 mm from ceiling		
	0.49 0.49 0.63 0.83 0.97 0.99 0.96 0.96	0.93	0.86
2326	Ceilings, 100 mm thick, 200 mm from ceiling		
	0.49 0.49 0.64 0.89 0.98 0.99 0.96 0.96	0.95	0.88
2327	Walls, 50 mm thick, directly against wall, with 0.05 mm PE-foil		
	0.2 0.2 0.63 0.99 0.95 0.83 0.66 0.66	0.92	0.85
2348	Walls, slotted 13 mm gypsum board (12%), 106 x3 mm2 on studs and mineral wool		
	0.2 0.2 0.22 0.71 0.99 0.55 0.42 0.42	0.75	0.62
2349	Walls, perf. 13 mm gypsum board (11%), d = 5 mm, on studs and mineral wool		
	0.18 0.18 0.32 0.71 0.99 0.5 0.29 0.29	0.73	0.63
2350	Ceilings, perf. 27 mm gypsum board (16%), d = 4,5 mm 300mm from ceiling		
	0.45 0.45 0.55 0.6 0.9 0.86 0.75 0.75	0.79	0.73

Ingolf Bork at PTB in Germany has a large data base on acoustic absorbers. This database can be found at the following e-mail link:

http://www.ptb.de/de/org/1/14/1401/_index.htm

APPENDIX C

The below mentioned noise control measures effectively reduces the BN in conventional as well as smart classrooms resulting in good acoustical condition and improved speech intelligibility.

System/Equipment	Noise Control Measure
HVAC	• Selection of quieter HVAC system • Proper duct lining, layout and design for attenuation of system noise transfer • Control of duct borne noise • Selection of quieter fans and assemblies • Proper selection & placement of diffusers • Optimal air flow rate with controlled noise generation • Regular & periodic maintenance
Lighting Fixtures	• Usage of general lighting with compact fluorescent lamps • Ballast free lighting fixtures • Periodic maintenance & replacement of assemblies
Instructional Equipment	• Selection of quieter equipment • Verification of equipment generated noise before ordering • Regular servicing of equipment
Wall Systems	• Selection of high frequency & vibration attenuating wall system • Rigid joinery and leak proof walls • Restrict externally transmitted noise
Openings	• Rigid and airtight solid openings • Lined and sealed intersections of the openings